

Quarterly Progress Report No. 11  
for the period: 1 January - 31 March 1993

## Automated Satellite Cloud Analysis Tactical Nephanalysis

Procurement Instrument:

F19628-90-C-0112

Submitted to:

Air Force Phillips Laboratory Geophysics Directorate  
Atmospheric Sciences Division  
Satellite Meteorology Branch  
Hanscom AFB, MA 01731

Submitted by:

Atmospheric and Environmental Research, Inc.  
840 Memorial Drive  
Cambridge, MA 02139

Prepared by:

G. B. Gustafson  
AER TACNEPH Co-Principal Investigator

## 1. Program Summary

This research and development program will produce a tactical nephanalysis computer program that will provide gridded fields of cloud amount and altitude from only those sources of data available in a Mark IV-B Tactical Terminal System. Specifically, the program must be able to successfully operate over a range of conditions including occasions when only sensor data from either the DMSP or NOAA polar orbiting satellite systems are available. Software development will require new algorithm development, validation, testing, and maintenance. Nine tasks have been identified as necessary to successfully complete the program requirements:

- 1) Mark IV-B database tasks including expansion of the AIMS database management software, AVHRR data acquisition, Earth location and remapping of satellite imagery, optimal interpolation of point source data, and implementation of image processing capabilities;
- 2) evaluation of the utility of SSM/I surface temperature retrieval algorithms for cloud discrimination over varying thermal backgrounds;
- 3) evaluation of SSM/I cloud amount algorithms;
- 4) development of nephanalysis and surface temperature retrieval algorithms for OLS and AVHRR data that will operate over different levels of data availability and reliability in a tactical environment;
- 5) evaluation of the utility of SSM/T derived vertical temperature profiles for assigning cloud top altitude;
- 6) development of improved algorithms for estimating cloud thickness and cloud base altitude from satellite sensor data only;
- 7) development of improved quality control and algorithm tuning procedures to support interactive manipulation and monitoring of nephanalysis results;
- 8) implementation of techniques to process surface based cloud observations and merge them with satellite derived analyses;
- 9) development of a tactical nephanalysis computer program that will implement algorithms and techniques derived from the previous tasks so as to produce a consistent cloud analysis independent of the mix of available satellite and conventional data.

In addition to the 9 functional tasks described above, AER has been tasked to provide real-time access to NOAA and DMSP polar-orbiting satellite data in support of TACNEPH algorithm development and validation. Specifically AER will provide AVHRR, TOVS, TIP, and ARGOS data from the NOAA TIROS satellites and OLS,

SSM/I, and SSM/T data from DMSP. To accomplish this, two complete satellite receiving and processing ground stations have been installed and interfaced with existing computers at the Phillips Laboratory. The ground stations are both TeraScan systems from Sea Space Inc. and include real-time data ingest capabilities plus software for standard image processing, analysis, and display. Both NOAA and DMSP systems are currently providing continuous real-time access to the sensor data.

A four year combined effort between AER and PL is underway to complete the project, a schedule of the estimated start date, duration, and progress for each task is presented in Figure 1.

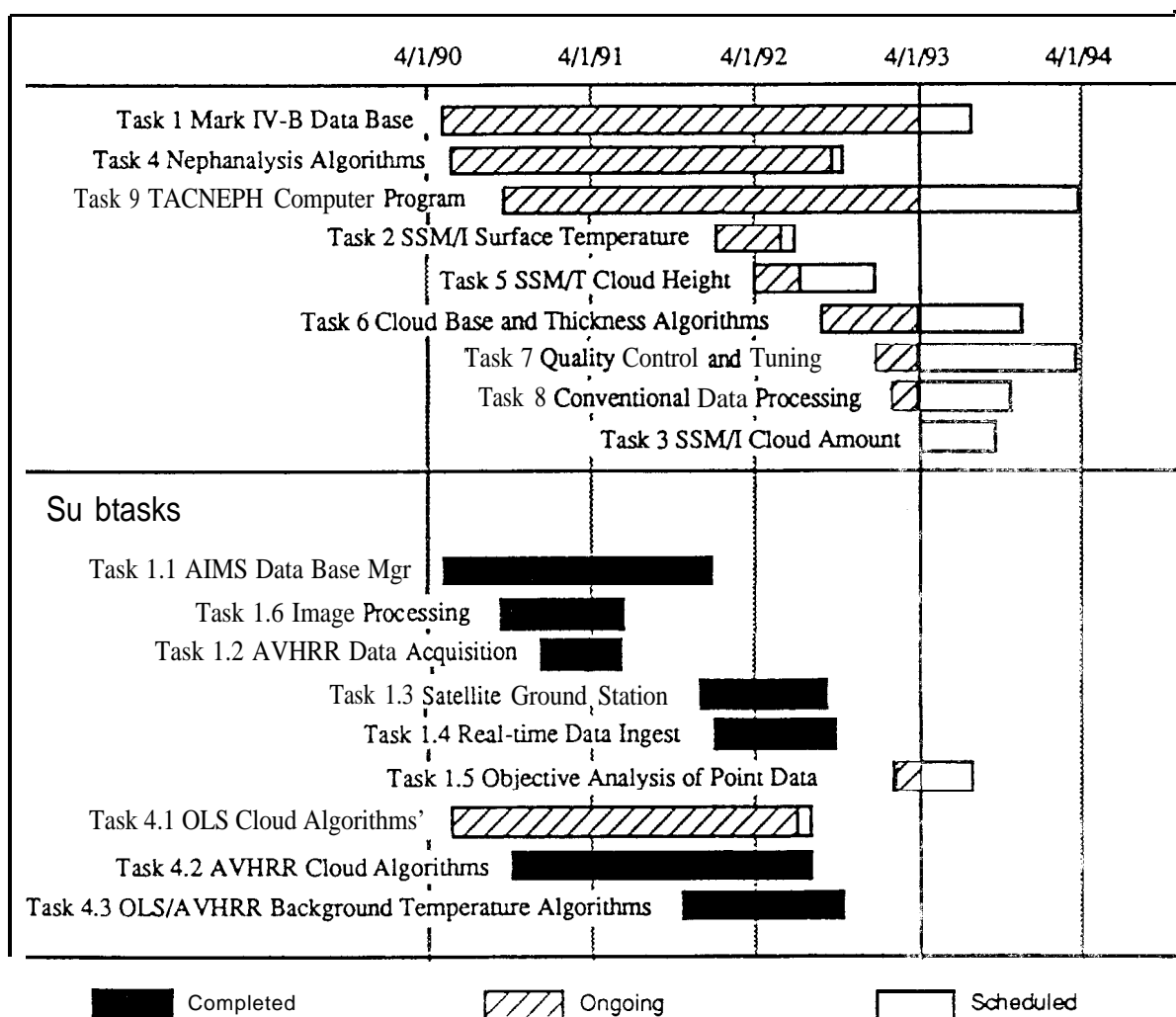


Figure 1 Revised TACNEPH task schedule with subtask breakdown.

## 2. Progress During the Reporting Period

Two new tasks and one subtask were started during the reporting period: Task 7, quality control and tuning; Task 8, conventional data processing; and Subtask 1.5 ingest of point data into the TACNEPH database. One subtask was completed: Task 4.3, OLS and AVHRR background surface temperature retrieval algorithms. Work progressed on five ongoing tasks: Task 2, estimation of OLS clear scene temperature from SSM/T; Task 4, nephanalysis algorithm development, with one subtask in progress: Task 4.1 - OLS cloud detection; Task 5, evaluation of SSM/T derived temperature profiles for cloud height assignment; Task 6, algorithm development for retrieval of cloud base anti thickness from satellite data; and Task 9, TACNEPH computer program development. Ongoing and completed tasks and subtasks are identified in the updated program schedule contained in Figure 1.

### 2.1 New Tasks

The Initial Task Review (ITR) for Task 7, quality control and tuning, was held on 3 February 1993 and is described in the meeting report dated 9 February, 1993. Work on this task is to be divided between development of quality control flags and tuning options. Quality flags will be designed to provide an assessment of the relative accuracy or reliability of a given analysis. Separate flags will be generated for total cloud and low middle, and high cloud. The main objective of the task is to determine what objective criteria should be used to measure algorithm accuracy. Several quantifiable measures are under consideration including the strength of the cloud signal (i.e., how close to the cloud threshold is the measured quantity), the number of tests that separately detect cloud, and the suitability of the analysis for a particular type of cloud (e.g., visible data for cirrus or thermal IR for low stratus). Tuning options are designed to provide a user with controlled access to the algorithm mechanics and with guidance on how the options are to be applied. Much of the discussion at the ITR centered on how to provide a user with little or no knowledge of the cloud analysis algorithm, or even meteorological satellite data analysis, with a tuning mechanism that would be useful and easily understood. The approach is to limit what the user can do to fixed adjustments to modify the algorithm sensitivity to low, middle, and high cloud. The available options are analogous to three dials, each with three settings. Each dial corresponds to a different cloud layer: low, middle and high. The center dial position corresponds to the optimal sensitivity setting for that layer, that is the setting determined to most accurately detect cloud without over

analyzing. One position on either side will allow a relative increase in sensitivity (with the possibility with an increase in false alarms) and on the other a relative decrease. This should provide the user with sufficient control to adjust the algorithm sensitivity to match a particular application.

A combined ITR for Task 8, conventional data processing and Subtask 1.5, objective analysis of conventional data, was held on 24 March 1993 and is described in the meeting report dated 29 March 1993. Conventional data process is not supported on the Mark IV-B so that work on this task would be considered a post-processing option rather than an integrated module in the TACNEPH algorithm. The main consequence of which is that conventional data can not be used to adjust the cloud detection thresholds used in the analysis algorithms, but rather can only be used to modify the final analysis. The requirements set at the ITR are to investigate using conventional data available on AIMS to modify the TACNEPH results following the approach of the RTNEPH Merge processor.

## 2.2 SSM/I Surface Temperature Retrieval

In preparation for implementation of a government furnished SSM/I surface temperature retrieval algorithm on the AIMS system, AER has been investigating the SSM/I antenna pattern correction (APC) provided on the TACNEPH DMSP ground station computer. As reported in the previous progress report, there was some uncertainty about whether the APC implemented on the ground station was consistent with the APC technique used on the Mark IV-B. A formal request has been made through the DMSP SPO to obtain information from LAD on the form of the SSM/I APC used on the Mark IV-B to insure consistency with the techniques used for TACNEPH. At this time no information has yet been received. However, a similar request to Capt. Tom Neu at AFGWC was acted on and a copy of the SSM/I APC routine used operationally at AFGWC was received during the reporting period. Comparisons of the AFGWC and TACNEPH APC algorithms revealed somewhat different implementations of level 2 corrections used in the APC algorithms, however, corrected brightness temperatures obtained from the two algorithms showed good agreement over a range of conditions.

At the end of the previous reporting period source code listings of the SSM/I surface temperature retrieval program developed for the RTNEPH program were received from AFGWC. These listings make up the GFE algorithms that are to be evaluated for TACNEPH use under Task 2. The technique is a two step linear regression algorithm

used to predict an OLS IR clear scene brightness temperature from the corresponding SSM/I temperatures. A series of linear coefficients are applied to the seven SSM/I channels to first characterize the background type and then, based on the background, a second set of coefficients are used to predict the clear scene OLS brightness temperature. This algorithm is potentially useful for TACNEPH since an accurate prediction of the OLS clear scene temperature could replace the adjusted surface temperature climatology in the single and two channel OLS nephanalysis algorithms.

The SSM/I clear scene temperature algorithm was successfully implemented on AIMS and the TACNEPH database was modified to accommodate the resulting temperature estimates. However, as also reported last quarter, the only regression coefficients provided by AFGWC were developed for the F-8 satellite. Personal communication with Capts. Norm Mandy and Tom Neu have revealed that at present the F-8 coefficients are all that is currently available. New software is being developed at AFGWC to support generation of coefficients for the F-10 and F-11 satellites but they will probably not be available before summer. Since the decryption device PL obtained for the TACNEPH ground station only has keys for F-10 and F-11, the clear scene temperature algorithm could not be tested on F-8 data. However, it was tested on F-11 data using the F-8 coefficients. Results for both the surface type classification and temperature retrieval portions of the algorithm were poor. The surface classification could not even accurately discriminate land from water backgrounds and temperature values frequently differed from coincident OLS clear scene brightness temperatures by greater than 30 K. Additional conversations with Capt. Neu confirmed that the disappointing performance of the algorithm was probably due to the use of F-8 coefficients with F-11 data. Since it seems pointless to perform an evaluation of SSM/I derived clear scene temperatures using these coefficients, further work on this has been postponed until new coefficients are available.

### 2.3 Nephanalysis Algorithm Development

Work during the reporting period was concentrated on the OLS algorithm. Analysis of clear scene statistics developed from comparisons of OLS brightness temperatures with corresponding surface temperature climatologies showed that some cloud-contaminated pixels were not being screened out by the cloud clearing algorithm. This resulted in the assignment of surface temperature climatology corrections used in the IR algorithm that were too large causing a negative feed-back on the entire cloud detection process. Cloud-contaminated pixels incorrectly used to update the clear scene temperature

statistics increased the expected range of clear scene temperatures to include values that were too cold. The result was a progressive loss of sensitivity to low cloud which in turn fed back into the next set of clear scene statistics. Two changes were introduced to correct this problem. First the cloud clearing criteria were stiffened to reduce the number of cloud contaminated pixels that were being missed by the cloud clearing algorithm. The second was to modify the clear scene statistics program to limit the magnitude of the limits change from one day to the next.

Currently, the OLS histograms are being monitored daily through the use of the visual display routine called IR\_HISTO. Before the changes were introduced some daily histograms showed a bias toward cold numbers superimposed on the normal bell shaped distribution. In all cases where this occurred, inspection of the original analysis file revealed cloudy pixels that were missed by the algorithm. Since the changes all histograms have displayed a normally distributed shape. Thus the rotating histogram database has proven effective in two ways: 1) to serve as an indicator of the natural variability between climatological estimates of surface temperature and satellite measurements and 2) as a quick diagnostic of OLS algorithm performance.

A modification was also made to the way data are collected in the histogram program. Previously the routine, which depends upon the OLS algorithm analysis for cloud/clear information, was run in a post-processing mode separate from the cloud analysis algorithm. It was decided to incorporate the program directly within the OLS algorithm so that collection of clear scene statistics is now a by-product of the cloud analysis. With the merging of these two routines came several changes. Previously the satellite scene was divided into 16x16 pixel subsets and, if the entire subset was cloud free, the average temperature difference over the pixel array was used as a single data point in the histogram. While this approach provided generally good results, some problems obtaining a sufficient number of data points to fill the histogram occurred on very cloudy days. To reduce the impact of several cloudy days in a row, the division of the satellite scene into subset boxes was eliminated and clear scene statistics are now accumulated on a pixel-by-pixel basis. This change had the effect of greatly increasing the number of points saved in each histogram and has effectively eliminated days that are discarded due to too few clear data points on cloudy days.

The clear-scene background brightness database is currently being updated with data from the F-11 satellite passes but is not yet completely filled. A post-processing

routine is currently being run using output from the OLS nephelometer analysis algorithm to update the database, but it is expected to be incorporated within the algorithm early in the next reporting period. Problems interpreting visible data collected near the terminator have slowed testing of the visible data part of the OLS algorithm. These problems have generally been caused by unknown changes in the on-board gain control of the sensor and shifts between the PMT and visible sensor over the regions of interest. However, as northern hemisphere summer approaches the visible sensor data are becoming more consistent and work is progressing.

#### 2.4 Evaluation of SSM/T Derived Cloud Height Assignment

Late in the reporting period, two tapes containing source code listings of the SSM/T temperature profile retrieval program were received from The Aerospace Corporation. These make up the government furnished algorithm that is to be evaluated for usefulness in assigning cloud height within TACNEPH. Progress on this task has been limited to decoding and input of the tape data and initial work at deciphering the source code to extract the algorithm. While very little documentation on the program was received with the tapes, the source code is well commented and progress is being made. Also included on the tape were several data files containing 8th mesh geography and terrain, 1000MB height D-values, numerous coefficient files, and the D-matrix listings. These are assumed to be used by the SSM/T retrieval program and are maintained on-line.

#### 2.5 Cloud Base and Thickness

The approach used in this task is to infer cloud optical thickness from satellite measurements of visible and near infrared radiance data. Reflected radiance is dependent on cloud optical thickness as well as sun sensor viewing geometry, cloud particle size distribution and phase. Particle size and phase can not be measured directly but are inferred from cloud type. Optical thickness is used to calculate physical thickness which is in turn used with cloud top information based on infrared emission to estimate base.

A radiative transfer simulation model is used to calculate channel radiances as a function of cloud thickness and cloud type. Atmospheric properties such as gas absorption profiles and aerosol extinction profiles are computed using LOWTRAN7. Cloud properties (optical thickness, single scattering albedo, and angular scattering function) used as input specified from a cloud type dependent modified gamma droplet size distribution are computed by a Mie scattering program (MIE). The output of LOWTRAN7 and MIE are input to a discrete ordinate method (DOM) multiple scattering radiative transfer



algorithm which computes the expected radiance. Based on these calculations a table of channel radiance versus cloud thickness has been generated for six model cloud types: cirrus, altostratus, low stratus, altocumulus, stratocumulus, and fair weather cumulus.

For each of the six cloud types the AVHRR radiance in channels 1-3 was simulated for five different cloud thickness values, and four different albedo values for the background. The model computed radiances are compared with the corresponding observed radiances in an AVHRR image for each cloud type and used to determine the cloud thickness of all the pixels in the image. Work on an appropriate cloud typing algorithm is continuing. For purposes of testing the radiative transfer approach, cloud type is manually identified.

## 2.6 TACNEPH Computer Program Development

Work progressed on validation of the AVHRR nephanalysis algorithm. The validation work continued to follow the plan described in the previous contract progress report. Since no additional guidelines have been received from the Air Force, the scope of the validation effort remains unchanged. AVHRR data collected from the PL ground station for June, September, and December of 1992 over two regions of interest (Figure 2) for three times of day are being used as case study data. The sensor data are independently analyzed for cloud using the objective TACNEPH algorithm and a subjective manual

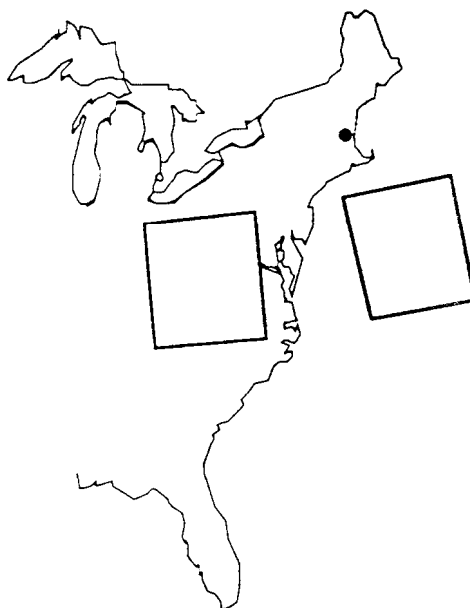


Figure 2 Data collection regions of interest used in the AVHRR algorithm validation program.

interpretation. Cloud/clear results from both analyses are entered into the AIMS computer system and objectively compared. Validation statistics are based on these comparisons.

Since the last reporting period, the interactive program developed to aid the manual analysis (TBLANK) has been used extensively to analyze the case study data. Additional options have been appended to the utility to accommodate the analyst's suggestions as they use the program to create the manual analysis files. Among these additional options are various new update options that affect the way pixels information is entered into the analysis. These options can be used in conjunction with each other, and often eliminate the need to remove data points that are erroneously entered into the analysis as cloudy during an intermediate step (recall that the manual analysis is an iterative procedure). Another new feature is the ability to generate a tabular listing of the data values of all sensor channels at a particular pixel location within a satellite image. This viewing option is supported by a mouse driven graphical user interface which allows the analyst to position a cursor directly over a pixel of interest and retrieve the digital values of each sensor channel. If desired, the analyst can then use the mouse to set a threshold based upon the values that are retrieved. This shorthand adjustment to the blanking threshold provides both a qualitative and quantitative method for setting optimum cloud/clear thresholds.

In addition to the new features of TBLANK, packing and unpacking utilities were developed for archival purposes. Because of the way the PL imaging computers are configured TBLANK produces an 8-bit cloud analysis output yet the result is binary. A new bit packing utility compresses the 8-bit data files to a fraction of their original physical storage size. To view the compressed results as an image, an accompanying unpacking utility was developed to reconstitute the eight-bit cloud truth image.

The TBLANK utility described above was used in two distinct phases of the validation of the AVHRR multispectral automated analysis routine. First, manual analyses were performed on five consecutive case study days from each of the daytime, nighttime, and terminator passes for both ROI areas to support collection of clear-scene statistics needed to initialize the nephanalysis model. Histograms of the differences between the sensor data and the corresponding climatological values were saved in a rotating clear-scene database which was modeled after the real-time database described in previous reports. The automated multispectral analysis routine was then run on data from subsequent days using composite thresholds based on these initial five days. From then on the clear-scene statistics were updated in the normal way using results obtained from the automated analyses. Automated analyses were collected until a minimum of ten histo-

grams were established. The second use of the TBLANK utility was to generate manual cloud analyses for the remainder of the case study days that were then used in the algorithm comparison routine.

To assist in the collection of statistics of the manual and automated analysis results, a routine called STATS was created which can access statistical data files through the TACNEPH database. This routine divides each analysis file into square pixel subsets of a specified size and generates comparison statistics based on cloud values calculated over each subset, as well as statistics based upon the analysis in its entirety. Statistics were collected and saved for pixels subset sizes of 16x16 and 32x32 to observe the affect of varying subset sizes on the correlation between the two analyses. A peripheral routine called READ-STATS was developed to prints the recorded statistical information in tabulated form (see Figure 3). Statistics were collected for each individual case day, as well as composites for each combination of month and time of day (e.g., June terminator cases).

To assist in the interpretation of the comparison data, histograms and scatter plots were created for each individual case, as well as for the composite sets. Scatter plots consist of paired data based upon the percentage cloudiness of each subset box in the manual and automated analyses (see Figure 4). The data were linearly ~~regressed~~, and information about this regression was included directly on the plots to indicate the correlation between the manual and the automated analyses. Histograms ~~were created~~ based upon the cloud percentage differences between each manual ~~analysis subset box~~ and its corresponding automated analysis subset box (Figure 5).

```
$ RUN READ-STATS
Enter entry number: 4010
Enter subset box size: 16
=====
TDB entry number: 4010
Subset box size :      16
Number of subset boxes: 15 12
Mean subset box %cloudiness for manual analysis:  47.61
Mean subset box %cloudiness for automated analysis: 49.90
Mean difference %cloudiness for (automated minus manual): -2.29
SD about the mean difference:      6.5916
%RMS error: 16.95
Both clear:  45.07%    Both cloudy: 42.53%    Disagree: 12.35%
Manual only: 7.32%    Automated only: 5.03%    Both: 87.65%
=====
```

Figure 3 Sample statistical output from the READ-STATS program for one case study day.

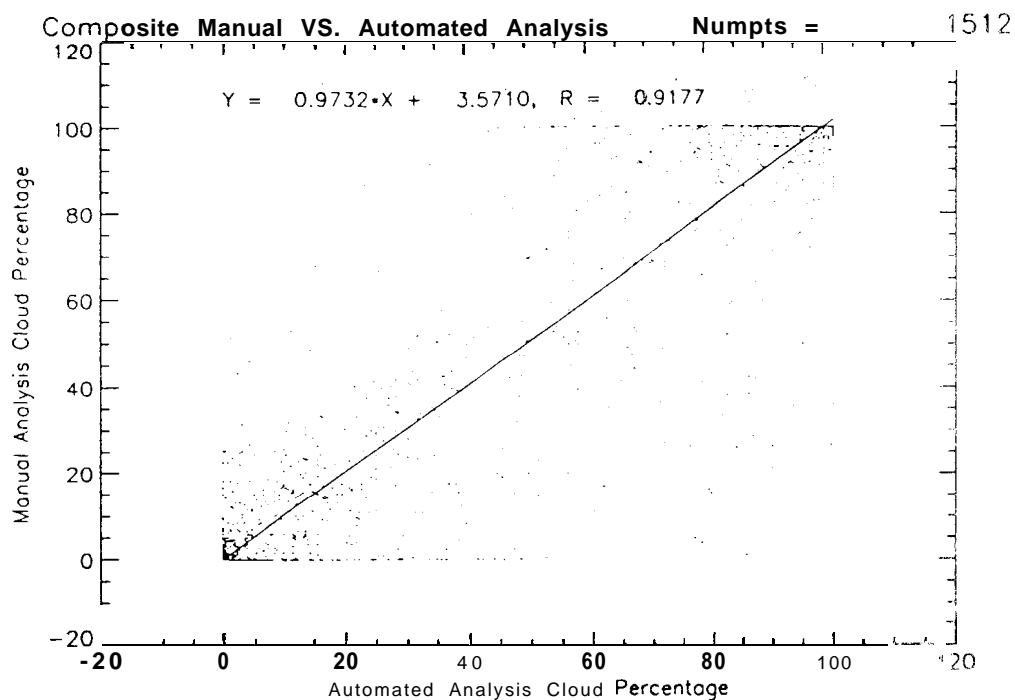


Figure 4 Sample scatter plot of fractional cloud amount obtained from the automated TACNEPH algorithm and manual analysis for one case study day.

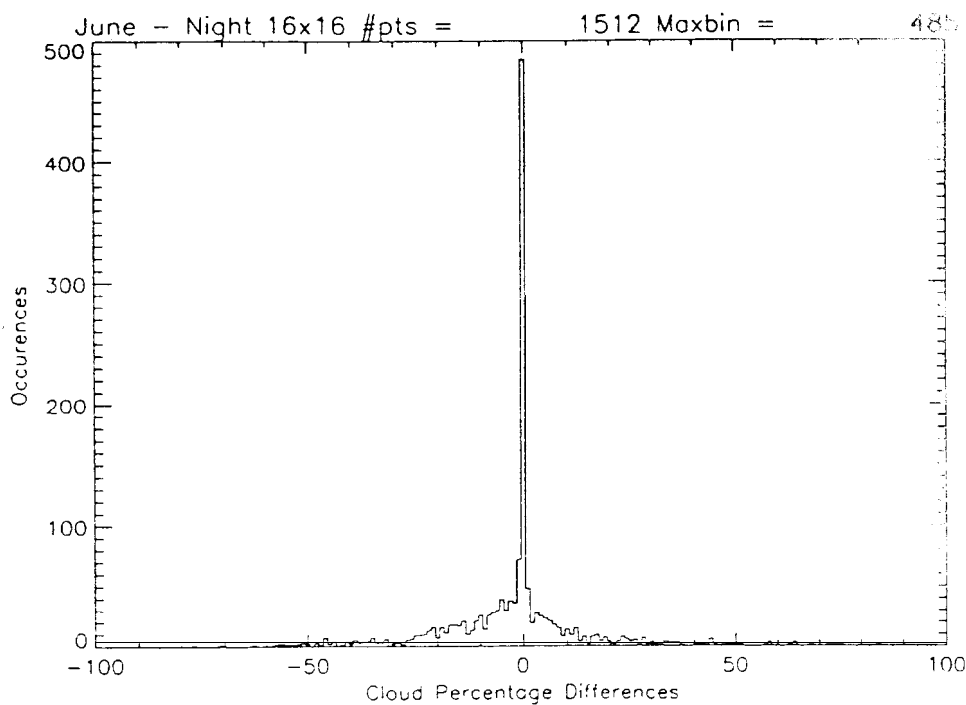


Figure 5 Sample histogram of differences in fractional cloud amount obtained from the automated TACNEPH algorithm and manual analysis for one case study day.

Currently, the entire validation process has been performed for all June and September cases (i.e., approximately 120 cases). Manual analyses of the December cases are underway and statistical analyses are expected to be completed within the next reporting period. Collection of March data will also start in the next reporting period. March of 1993 data will be used since the AVHRR ground station as not yet operational in March of 1992.

Data collection for cloud/clear results has been completed for the June and September cases using archived NOAA-11 and NOAA-12 passes. Analysis was begun for 5 days of data for terminator, daytime, and nighttime passes from the June case. NOAA-11 and NOAA-12 passes stored on tape were unloaded and listed on the UNIX system. Each tape contains two or three days worth of NOAA-11 and -12 passes with each pass being assigned a file number. Passes containing; terminator, daytime, nighttime images for the land and water sites were then chosen. Once a determination was made that a pass fit the criteria for site location, time, etc. the image was transferred to optical disk for access on the AIMS system. Each case transferred to the AIMS system for analysis was registered in TDB and assigned an entry number.

Objectives of the manual analysis tie to accurately locate and classify cloud/clear areas from each satellite pass using all visible and infrared channels that are available from the AVHRR. As described above, the TBLANK utility package enables the user to build a final composite analysis using various methods to segregate and split portions of an image. Separation and splitting of imagery greatly enhances the accuracy of the cloud analysis as opposed to analyzing the image in its entirety. Analysis of the June data are nearly complete, processing of September and December cases is expected to be completed during the next reporting period. Collection of March data will have to wait until March of 1993 since the AVHRR ground station was not yet operational in March of 1992. A similar procedure will be applied to the OLS data for validation of that algorithm.

### 3. **Plans for the Next Reporting Period**

Work on the OLS algorithm development is essentially complete and the FTR will be scheduled early in the reporting period. Validation of the AVHRR algorithms will continue along with collection of OLS validation data. Implementation of the SSM/I algorithm should be completed and testing in the TACNEPH algorithm will begin. Work on the cloud thickness algorithm will continue with testing of the three channel radiance

tables relating cloud optical depth to AVHRR channel radiance. Algorithm tuning work will continue with identification of internal thresholds that correspond to dial settings and evaluation on real data.

#### 4. Other Issues

A paper entitled "Validation of infrared cloud detection algorithms developed for TACNEPH" by Gustafson, Isaacs, and Sparrow from AER and Bunting and d'Entremont from PL was submitted to the SPIE Conference on Passive IR remote sensing of clouds and the atmosphere, to be held 13-16 April, 1993. A copy of the paper is attached.

An one year extension to the software support agreement for the TACNEPHRPT satellite ground station was purchased from Sea Space, Inc. and a one year extension to the software support agreement for the TSSNET networking software used to link the ground station with AIMS was purchased from Thursby Software, Inc.

No research or analysis failed.

Of the total funds of \$1,026,776 allocated for 48 months, approximately 80% have been expended after 36 months; approximately 80% of the work has been completed. Note that \$226,545 of this expenditure has been for acquisition and installation of satellite ground station equipment and expenditure of funds allocated for research and development is on track. Detailed fiscal data are available separately in the monthly Contract Fund Status Reports.

# **Validation of infrared cloud detection algorithms developed for TACNEPH**

Gary B. Gustafson, Ronald G. Isaacs, Jeanne M. Sparrow

Atmospheric and Environmental Research, Inc. (AER)  
840 Memorial Drive, Cambridge, MA 02139, USA

James T. Bunting, Robert P. d'Entremont

Phillips Laboratory  
29 Randolph Road Hanscom AFB, MA 01731-3010

## **ABSTRACT**

A multi-year research and development program is underway to develop an automated cloud model known as TACNEPH for use by the Air Force at tactical sites. Significant features of this model include the ability to analyze real-time DMSP/OLS and NOAA/AVHRR data using only the limited resources of transportable tactical ground stations and to automatically adapt to changes in the available data mix. No supporting data from a center are available (e.g., upper air temperature and moisture fields, surface reports). To satisfy these requirements it was necessary to develop separate algorithms for each sensor platform. An infrared algorithm developed for DMSP data relies on an estimate of the clear scene radiative brightness temperature based on a dynamic correction to a surface temperature climatology. A separate NOAA IR algorithm is an adaptation of the multispectral approach of Saunders and Kriebel. Both algorithms are designed to improve cloud detection capabilities over the current Air Force operational RTNEPH model, with particular emphasis on low cloud.

A major aspect of the TACNEPH development program is the validation of the cloud algorithms over globally varying conditions. Since there is no universally accepted source of ground truth data for cloud, it was necessary to develop a validation procedure based on available data sources. Use of surface cloud observations or intensive field observing programs (e.g., FIRE) alone were rejected due to limitations in coverage area and inherent difficulties in comparing satellite based cloud estimates with surface based observations. Algorithm validation is instead based on subjective man/computer analysis of the input satellite sensor data using any available additional data sources as guidance. A formalized procedure for performing the manual analysis has been developed that exploits the interactive display and image enhancement features of modem image processing systems along with data visualization techniques designed to present both multispectral sensor data and manual analysis results in an easy to interpret digital raster form. Validation results for TACNEPH infrared algorithms will be presented for selected case studies used to capture the globally and seasonally varying conditions the algorithms are expected to encounter.

## **1. INTRODUCTION**

A four year research and development program is underway at the Air Force Phillips Laboratory to develop an automated cloud analysis model known as TACNEPH (for tactical nephalanalysis) designed to be run in the field on transportable satellite receiving ground stations. Significant features of the model are the ability to analyze both DMSP/OLS and NOAA/AVHRR sensor data in real-time to produce gridded fields of fractional cloud amount and height. Since the algorithms are designed for field use available resources are limited to the capabilities of the ground station systems. The principal limitations are the type and amount of data that are available. The ground stations are capable of receiving direct broadcast satellite transmissions and have limited capacity to store climatological information, however, no supporting data from a center are available (e.g., upper air or surface temperature and moisture fields, surface observations). Also the model must be able to automatically adapt to changes in the available data

mix. To satisfy these requirements multiple cloud analysis algorithms were developed. One and two channel algorithms developed for analysis of DMSP data rely on estimates of the clear scene reflectance and surface radiative brightness temperature to discriminate cloud. Separate NOAA algorithms are adaptations of the multispectral approach of Saunders and Kriebel (1988) and Karlson and Liljas (1990). All algorithms are designed to improve cloud detection capabilities over the current Air Force operational RTNeph model, with particular emphasis on low cloud and transmissive cirrus.

A major aspect of the TACNEPH development program is validation of the cloud algorithms over globally varying conditions. While TACNEPH is designed as a regional model, it must be relocatable since the transportable ground stations could potentially be located anywhere on Earth, thus the need for global validation. Unfortunately, for satellite nephanalysis purposes there is no universally accepted source of ground truth data for cloud, so it was necessary to develop a validation procedure based on available data. Use of surface cloud observations or intensive field observing programs (e.g., FIRE, ARM) alone was rejected due to limitations in coverage area and inherent difficulties in comparing satellite derived cloud estimates with surface based observations. Algorithm validation is instead based on comparison to computer aided manual analyses of the satellite sensor data. Any additional data that may be available (e.g., surface observations) is used for guidance. A formalized procedure for the manual analysis has been developed that exploits the interactive display and image enhancement features of 24-bit, full color image processing systems along with data visualization techniques designed to present both multispectral sensor data and manual analysis results in an easy to interpret digital raster form. Initial validation work using case study data has been completed for two seasons over the East central United States and the Atlantic Ocean.

## 2. CLOUD ALGORITHM DESCRIPTION

The approach to cloud algorithm development is illustrated in Figure 1 wherein multiple algorithms exist to satisfy the external constraints imposed by the data mix. As the amount or quality of satellite data decreases the algorithms automatically place increased reliance on locally available and stored databases. Conversely, as contingencies develop that decrease the reliability of stored databases the analysis program will switch to a processing level that is less dependent on supporting data. An important feature of this multilevel approach is the capability to perform simultaneous algorithm co-calibration in the field. The inherent algorithm redundancy that exists under conditions of full data availability can be exploited to intercalibrate one algorithm against another during off-peak periods. Algorithm intercalibration statistics can then be used to assign confidence levels to results obtained later during non-optimal data limited conditions.

Algorithms have been developed to accommodate the range of imager data obtainable from the OLS and AVHRR instruments. Two statistical threshold algorithms operate on single infrared thermal window channel data alone or in combination with a visible or near-IR channel (i.e., OLS-T and OLS-L; AVHRR channels 1 or 2 and 4 or 5). Daytime and nighttime AVHRR algorithms use all available channels simultaneously. This multispectral approach employs a decision tree structure to classify individual scene features (e.g., low cloud, cirrus, snow, sun glint) separately through evaluation of a selected set of spectral signatures at each branch. For the TACNEPH application spectral signatures are taken to be combinations of channel ratios, differences and absolute magnitudes. This approach has been used successfully in previous cloud detection applications (Saunders and Kriebel, 1988; Karlsson and Liljas, 1990) and is similar to ongoing work at NOAA (Stowe et al., 1991). Information on cloud type and cloud optical properties is produced as a by-product of the multispectral cloud detection algorithms. The TACNEPH cloud detection algorithms have been described elsewhere (Gustafson and d'Entremont, 1992; Isaacs, 1993) and will only be summarized here.



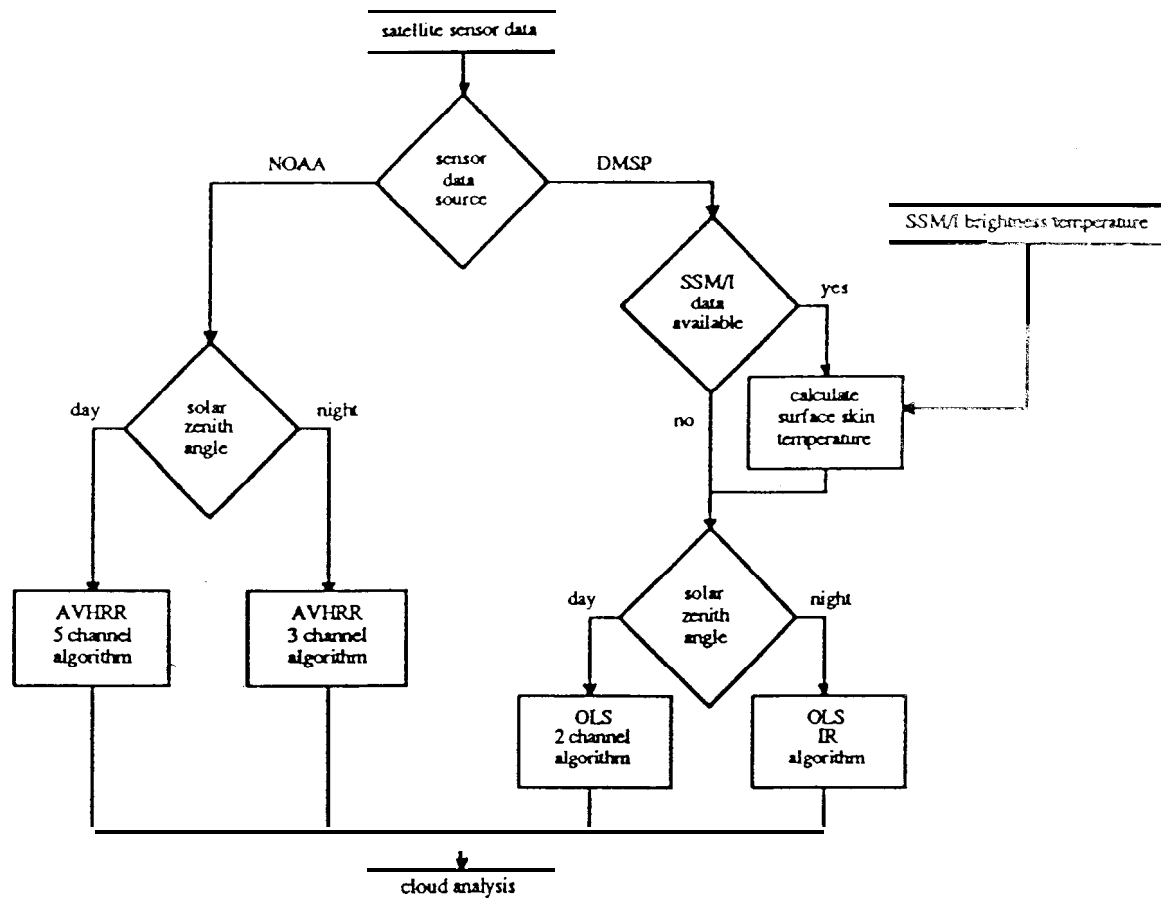


Figure 1. Schematic of TACNEPH multi-source cloud analysis approach.

The single and two channel threshold algorithms are designed to identify **cloud-filled**, **cloud free** and partially cloudy pixels within- the scene and to determine representative cloud top and cloud free background temperatures. This information is used to compute the required parameters for each analysis grid box, namely fractional amount and altitude. A threshold approach was selected because it is well suited to the TACNEPH environment where uncertainties in the available data (e.g., sensor calibration errors, stored data not representative of current conditions, variations in clear scene radiative characteristics, atmospheric transmission) cannot be accurately modeled. An empirically **derived dynamic** correction factor is used to account for all sources of error collectively without the need to **understand and** quantify the individual contributions. For TACNEPH, surface temperature **climatology data** adjusted by the correction factor, are used to predict cloud free satellite brightness temperatures. This value is then applied to the correct climatological temperature to discriminate **cloud filled** and **partially filled** pixels from the cloud free background and to calculate their relative contributions to the total cloud amount. While threshold algorithms that attempt to discriminate cloudy from cloud free pixels are **inherently incapable of** accounting for partially filled fields of view (FOV). This is illustrated in Figure 2a, where the partially filled FOV are misclassified as either cloud filled or cloud free. This problem is compounded by the fact that cloud boundaries tend to be amorphous and the actual definition of where they occur generally depends on the application. The TACNEPH algorithm attempts to minimize these problems by using two thresholds to define separate cutoff values for completely cloudy and completely clear pixel; (Figure 2b). Data points that lie between the two cutoff values are treated as partially filled (i.e., contain a cloud type). Estimation of the contribution of partially filled FOVs to the total cloud amount is accomplished through an energy balance equation adapted from the spatial coherence technique of Coakley and Bretherton (1982).

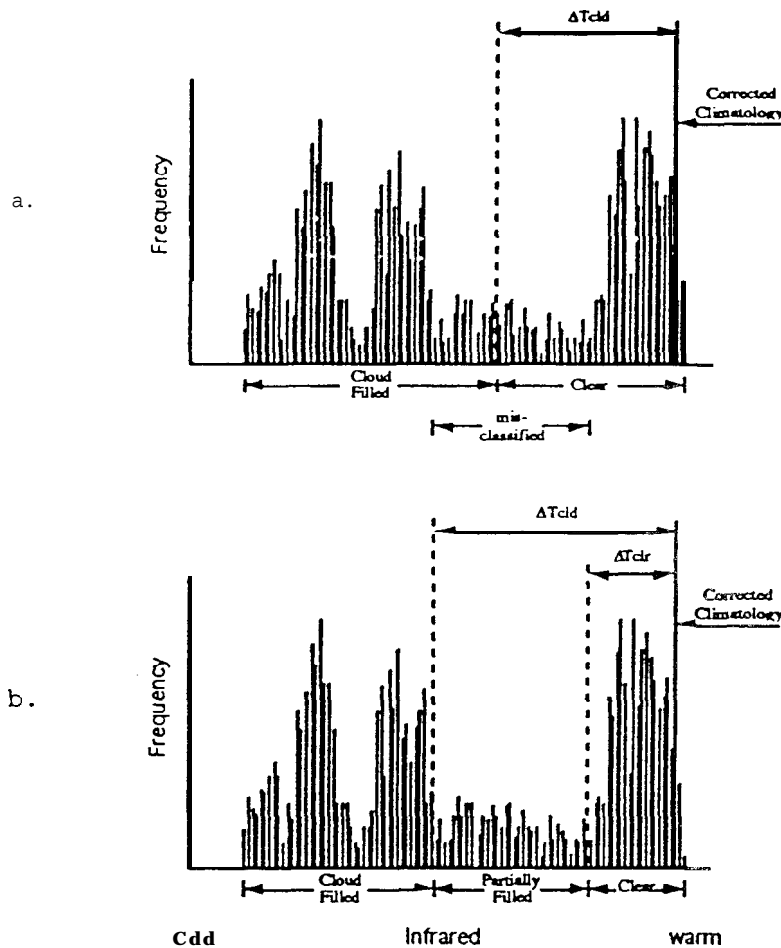


Figure 2. Histogram of infrared radiance for a partly cloudy, multi-layer cloud scene illustrating how (a) single threshold and (b) dual threshold techniques classify partially filled FOVs.

A two channel approach developed for the OLS during daytime is similar to the single channel algorithm described above but is applied in two dimensions. Conceptually the two channel approach is straightforward, data from both visible and infrared sensor channels are analyzed simultaneously using two pairs of cutoff values, one pair in each dimension. Data that are cold, bright, or cold and bright (relative to the respective cutoff values) are classified as cloud except over snow, ice, and desert backgrounds. Data that are both warm and dark are unambiguously classified as clear. Warm bright regions require an a priori clear scene classification to remove the ambiguity caused by the similarity in radiative signatures of backgrounds such as deserts and low cloud. Data points that fall between all four cutoff values are classified as partially cloud filled. Their contribution to total cloud amount is calculated geometrically and is assumed to be proportional to the normalized distance from both clear cutoff values in the space defined by the intersection of the four cutoff levels.

AVHRR multispectral algorithms use up to five separate tests that exploit different cloud spectral signatures. Each test is applied in succession and results are combined to classify the scene characteristics. Generally, tests that rely on reflected solar radiation (i.e., use channels 1, 2, or 3) can misclassify snow, ice and sun glint over open water backgrounds as cloud. The main exception are tests that use channel 3 data over frozen water backgrounds since ice and snow are relatively non-reflective at these wavelengths, however, sun glint affects all three channels. The problem of discriminating these problematic

backgrounds from cloud is also data constrained since no separate databases are available to help characterize the backgrounds, therefore snow, ice and sun glint algorithms were developed using the sensor data alone. Snow and ice are detected by comparing the solar component of daytime channel 3 data to channel 1 visible data. For cloud, both will be bright, however over snow and ice only the visible is bright. Specular reflection over water remains a problem despite knowledge of the solar and satellite observing geometry since glint can occur well away from the specular point depending on sea state and wind direction. The sun glint algorithm tests for a series of conditions that resemble cloud in the reflected solar tests but do not in tests that rely on emitted IR radiation only. However, this condition alone is not sufficient to detect glint since low liquid water clouds can exhibit the same characteristics. An additional criteria requires that the magnitude of the channel 3 data approach sensor saturation, a condition that normally occurs in glint conditions since the channel 3 radiance is very sensitive to even small amounts of reflected solar.

AVHRR cloud tests generally rely on channel differences or ratios to discriminate cloud signatures from those of terrestrial backgrounds. Due to the unique radiative characteristics of low clouds and fog at  $3.7\ \mu\text{m}$  relative to long wave IR channels, comparison of channel 3 and 4 brightness temperatures is a particularly powerful low cloud discrimination technique during both day and nighttime. At  $3.7\ \mu\text{m}$  liquid water clouds radiate as gray bodies whereas at  $11\ \mu\text{m}$  they are nearly black (d'Entremont et al., 1987). As a result, at night the lower cloud emissivity results in cooler channel 3 brightness temperatures relative to channel 4, however, during the daytime the combined emitted and reflected solar components cause the derived brightness temperature to be relatively warm compared to channel 4 where there is only emitted radiation. Additionally, due to the highly non-linear shape of the Planck function between channel 3 and 4 wavelengths, the relative contributions to the brightness temperature derived from the integrated measured over the relative channel bandpasses of (cold) cloud and (warm) backgrounds for partially filled FOV differs between the two channels. At  $3.7\ \mu\text{m}$  the warm background dominates the cold cloud and the derived brightness temperature is warmer than at  $11\ \mu\text{m}$ . This signature is useful for detecting broken and transmissive high (cold) cloud at night, particularly optically thin cirrus.

Other cloud tests use relative differences between the split visible (1 and 2) and split long wave IR channels (4 and 5). Relative visible and near IR clear scene albedo measurements will differ depending on background. Over water, both channel albedos tend to be low but enhanced aerosol scattering at channel 1 generally results in a slightly higher scene albedo. Over land the signature reverses except in cases of extreme aerosol loading since vegetated surfaces reflect preferentially in the near IR. Clouds tend to obliterate the background signatures and reflect approximately equally in both channels. However, the absolute magnitude of the measured channel 1 and 2 radiances can vary significantly over a scene depending on the relative reflectivity of the observed surface, solar geometry, and anisotropic effects. To cancel these effects out of the cloud detection algorithm the ratio of the two channels is used to discriminate the background signatures from the cloud. A cloud signature is assumed to be a ratio of approximately 1. Split IR channel data are used to detect ice cloud and small particles along both ice and water cloud edges regardless of time of day. Inter-channel brightness temperature differences are expected due to preferential water vapor absorption at channel 5 wavelengths, however, in the presence of ice the differences exceed the theoretically predicted amount. Inoue (1987) recognized that this departure was caused by unequal extinction from thin ice clouds at 11 and  $12\ \mu\text{m}$ , with the greater extinction occurring at  $12\ \mu\text{m}$ . Prabhakara et al. (1988) extended this signature to include both liquid water and ice clouds when the droplet or particle size was smaller than the channel wavelength. Saunders and Friebe (1988) developed a test to exploit these signatures through a theoretically derived look-up table of expected clear scene channel differences caused by preferential water vapor absorption at channel 5.

All of the above tests are well suited to the TACNEPH application since they do not require complicated radiative transfer calculations or frequent updating of supporting databases. In most cases the cloud signatures can be unambiguously inferred by simply contrasting one channel against another.

### 3. VALIDATION PROCEDURE

During the algorithm **development** process the cloud detection techniques were extensively tested by visually comparing the **algorithm results (displayed as a cloud mask color coded for each of the tests)** to the original satellite data. **However, a more quantitative** measure of algorithm accuracy was required before the algorithms could be **converted for operational** use. The only **sources** of data readily available for the TACNEPH validation study were DMSP/RTD and NOAA/HRPT direct broadcast ground stations at the Phillips **Laboratory** in Bedford, MA. The coverage area from **these** systems ranges over the eastern U.S. and Canada to the western North Atlantic. It is assumed that performance of the cloud algorithms is **dependent** on (at least) representative cloud types, scene illumination conditions, and background. To exercise the algorithms **over as broad a range of these** conditions as possible given the input data constraints and man power resources, two regions of interest (ROI) within the coverage area **were** selected to represent terrestrial and oceanic backgrounds (Figure 3). Data were collected for each ROI over 8-10 day periods from four seasons: June, September, December, and March; for daytime, nighttime and near terminator orbits.

Validation consists of an evaluation of algorithm accuracy based on a quantitative comparison of automated algorithm results with a corresponding manual analyses of the available satellite sensor data. The output of the manual analyses is used as truth for the purposes of these comparisons. This approach was selected since 1) there is no universally accepted source of ground truth for cloud and 2) it was felt that a manual analysis by an experienced analyst would provide the most accurate **and consistent truth** data possible for evaluating satellite nephanalysis algorithms. To support the manual analysis an interactive



Figure 3. Selected regions of interest for validation study; the land ROI covers the area 35-40 N latitude, 78-83 W longitude; the water ROI covers the area 35-40 N latitude, 73.5 - 58.5 W longitude.

routine was developed and implemented on dedicated image processing computers at the Phillips laboratory. The program assists an analyst to manually classify and catalog cloudcontaminated pixels in multispectral satellite imagery through a set of interactive man/ machine functions that support full color multispectral display, image enhancement, segmentation and thresholding. Actual delineation of cloud boundaries in a scene is accomplished through a technique known as threshold blanking. Here the analyst selects and displays one channel of satellite data as a raster image on a monitor and interactively raises or lowers a pixel intensity threshold on a selected subregion. The threshold is adjusted until it accurately delineates the cloud boundary as determined by the analyst. The magnitude of the threshold level is viewed on the monitor as a user selectable color shading of the image. For example, if the analyst chooses, say, a green shade then pixels with intensity levels below the current threshold will be displayed as shades of green while pixels above retain **their** original gray shading. This allows the user to see **where** the threshold level is set without obscuring features with intensity levels below that level. Threshold blanking was selected over other possible techniques because it was felt to be the most accurate way of transferring the analyst's realization into a digital form.

The manual analysis is performed on a selected subregion using imagery for from one sensor channel at a time. Since it is unlikely that a single threshold applied to a single sensor channel will accurately identify all cloud boundaries in a scene, the process is iterative. Typically different parts of a scene are most easily analyzed using different sensor channels (e.g., visible channel for dense liquid water clouds over dark backgrounds or long wave IR data for thin cirrus). Therefore the analyst has the **option** to repeatedly segment the scene in whatever way is most appropriate through interactive selection of optimal sensor channel and subregion combinations. The manual analysis procedure is represented schematically in Figure 4.

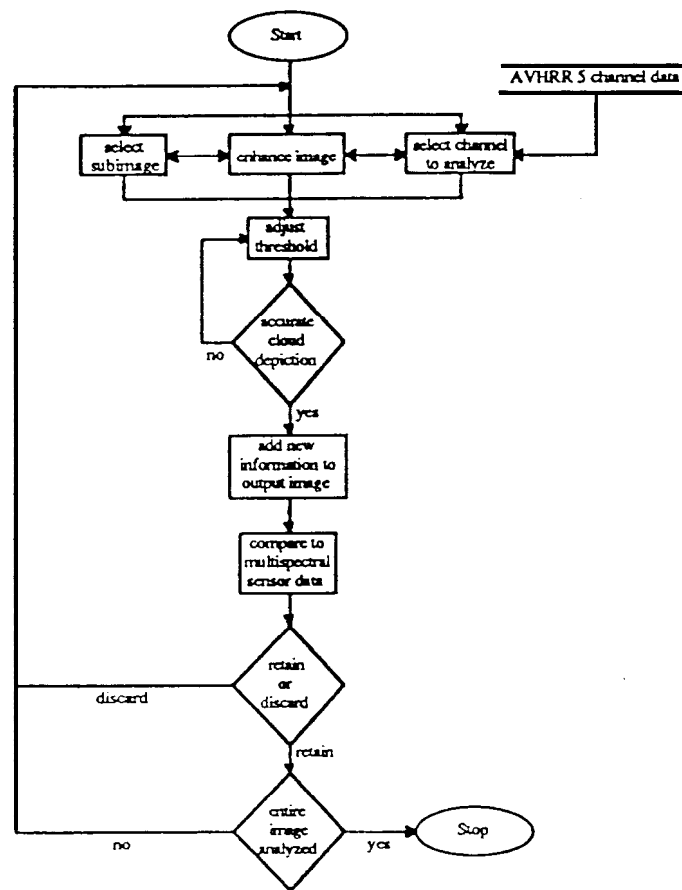


Figure 4. Schematic of AVHRR manual cloud analysis procedure.

Manual cloud analysis is performed as a single blind procedure since the analyst has no knowledge of the automated algorithm results but is aware of the algorithm characteristics. In addition to the satellite data the analyst also has access to conventional surface observations over the land background region of interest (Figure 3). Surface based reports of cloud cover are used only for guidance and never to replace the satellite data. For example, if an analyst suspected a fog or low stratus deck from examination of, say, a composite 3.7 and 11  $\mu\text{m}$  image, this could be confirmed by looking at surface reports from that area. However, a surface report of fog, without supporting evidence in the satellite imagery, -would not be extrapolated to the larger satellite scene.

#### 4. RESULTS

Final output products of both the manual and automated algorithm analyses are binary images depicting the cloud filled (1) and cloud free (0) regions of the scene on a pixel-by-pixel basis. Fractional cloud amount can be readily calculated for any selected grid size. Comparison statistics were computed over a 32X32 pixel grid selected to approximate the grid spacing that will be used in the operational implementation of TACNEPH.

Individual comparison statistics for June and September are summarized in Table I. A total of 60 scenes covering the regions identified in Figure 3 were analyzed through both the automate4 algorithm and the manual classification procedure. Statistics were compiled for mean cloud amount from the automated and manual analyses, mean cloud difference and standard deviation, and root mean square error. Results are stratified by satellite orbit and time of year. Statistics for December and March are still being compiled.

Table 1. Comparison statistics between automated and manual analyses for June and September case study periods.

	Automated	Manual	Difference	Standard Deviation	RMS	Box Count
June						
Day	54.4	54.2	0.2	8.0	22.5	2894
Night	49.1	53.7	-4.6	7.7	18.2	3024
Terminator	46.7	53.4	-6.7	8.8	25.0	3143
September						
Day	55.4	59.9	-4.5	5.5	14.8	4136
Night	73.5	72.4	1.1	10.4	26.5	3405
Terminator	70.2	68.8	1.3	5.6	14.9	2566

These preliminary results show good agreement for fractional cloud amount between the automated and manual analysis techniques for the summer and fall cases. RMS differences tend to imply a greater disagreement than mean differences or standard deviation due to the weight the RMS statistic gives to large errors. A relatively small number of missed clouds could have a disproportionate affect on the RMS magnitude (e.g., low cloud identified by the manual analyst but not detected by the automate algorithm will result in a 100% difference, the affect of which will be squared in the RMS calculation). Confirmation that the overall analysis accuracy is good can be obtained both from the comparison statistics in Table 1 and from histogram plots such as those contained in Figure 5. Composite histograms are computed for each of the cases in Table 1, and contain the frequency distribution of the magnitude of the difference between the automated and manual fractional cloud amount computed over each 32X32 pixel box in all analyzed scenes. Note that in each case the histograms have a characteristic spike at 0% disagreement and, as indicated by the standard deviation statistics in Table 1, most of the variance is within a few percent of that spike. Also noteworthy is the absence of even small spikes at the + or - 100% bins that would indicate a tendency for undetected or overanalyzed clouds. Most of the difference can be explained by inconsistencies in where the analyst and the automated routine established cloud edges.

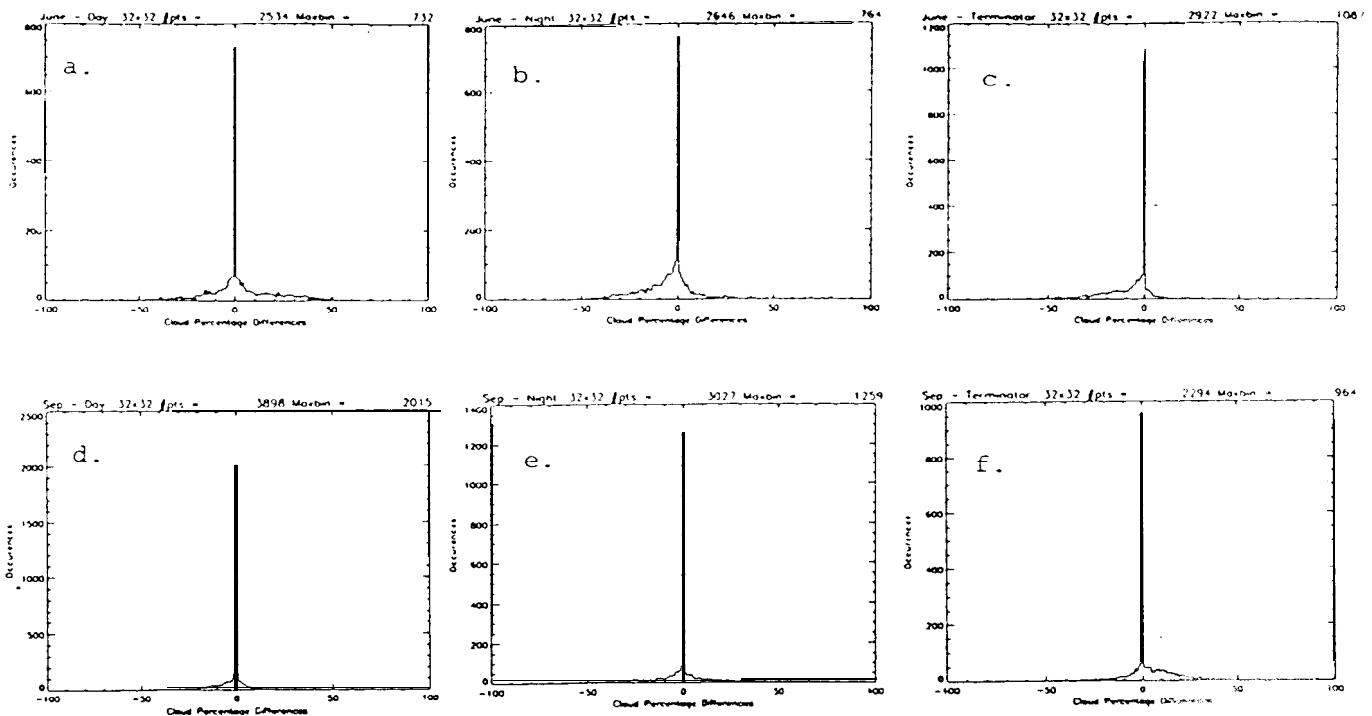


Figure 5. Histogram of difference (%) between manual and automated cloud analysis results for June: a) day, b) night, c) terminator and September d) day, e) night, f) terminator.

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# The Tactical Nephanalysis Program (TACNEPH)

## PROGRAM SUMMARY

**Satellite** Meteorology Branch  
Atmospheric Sciences Division  
Geophysics Directorate, Phillips Laboratory  
Hanscom AFB, MA 01731 - 5000

August 1992

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## THE TACTICAL NEPHANALYSIS PROGRAM (TACNEPH)

### 1. Overview :

The Tactical Nephanalysis (TACNEPH) program is a four-year research effort being conducted by the Satellite Meteorology Branch of the Phillips Laboratory Geophysics Directorate (PUGPAS) and sponsored by the Defense Meteorological Satellite Program (DMSP) Systems Program Office (SPO), Space and Missile Systems Center (SMC), Los Angeles, CA. The TACNEPH objective is to develop and validate a set of robust, relocatable regional cloud detection and analysis algorithms that generate gridded fields of cloud parameters using only the resources available on the MARK-IVB Tactical Terminal currently produced by Lockheed Space and Missile Systems in Austin, TX.

The required attributes of the TACNEPH analysis are autonomy, transportability, reliability, and optimal degradation. *Autonomy* means that the cloud analysis is performed without supporting input data from a central site such as the Air Force Global Weather Center (AFGWC) in Offutt AFB, NE. *Transportability* means that the TACNEPH cloud algorithms must operate within the constraints of tactical terminal ingest, computing, and display capabilities. *Reliability* means that an accurate cloud analysis will be produced at any location around the world. Finally *optimal degradation* means that TACNEPH algorithms will produce the most accurate analysis possible based upon available satellite data resources.

The data resources available to the Mark-IVB, and therefore utilized by TACNEPH, are the DMSP Operational Linescan System (OLS), Special Sensor Microwave Imager and Temperature Sounder (SSM/I and SSM/T, respectively), the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR). Limited conventional surface and upper-air observations may be available, and the TACNEPH is being designed to operate with or without conventional data. Data not used by TACNEPH are the NOAA High-Resolution Infra-Red Sounder (HIRS) and the Microwave and Stratospheric Sounding Units (MSU and SSU), and the GOES Visible-Infrared Spin Scan Radiometer (VISSR) and VISSR Atmospheric Sounder (VAS).

The cloud parameters that TACNEPH must generate are total cloud fraction (i.e., amount), cloud base, and top. For each layer of clouds the type, amount, and heights are also to be specified. The microphysical properties and radiative characteristics of clouds are not included as required TACNEPH parameters, except to the extent to which cloud phase can be inferred by type. The required cloud attributes must be generated in gridded field format for relocatable, regional areas anywhere on the globe.

The four-year TACNEPH development began in May 1990 and ends in April 1994. Semi-annual technical / programmatic reviews are required, nominally in September and April of each year. The first was in December 1990 and the second not until November 1991. The primary responsibility for carrying out TACNEPH belongs to the Satellite Meteorology Branch of the Phillips Laboratory, Geophysics Directorate (PL / GPAS ), Hanscom AFB, MA; POC is Mr. James T. Bunting, DSN 478 - 3495, (617) 377 - 3495. In-house support for TACNEPH consists of four man-years per year of government researcher and administration effort. This research is mainly focused on development of multispectral cloud detection and analysis techniques. Other responsibilities of GPAS include program management, reviews / report preparation, and delivery to the DMSP SPO of annotated TACNEPH cloud analysis algorithms for use in the Mark-IVB environment.

In-house contract support to GPAS is provided by Atmospheric and Environmental Research (AER), Inc., Cambridge MA under the management of co-principal investigators Mr. Ronald G. Isaacs ( (617) 547 - 6207 ) and Gary B. Gustafson ((617) 377 - 4510 ). The AER level of effort consists of four man-years per year. This support consists predominantly of development and maintenance of research grade TACNEPH computer software and also includes assistance in the development of cloud analysis techniques and in the acquisition and handling of real-time NOAA and DMSP polar orbiter data at Phillips Laboratory, Hanscom AFB.

## 2. Task-by-Task Program Synopsis

In this section a summary is presented of each of the nine major tasks of the TACNEPH program, complete with a statement of objectives and deliverables. Figure 1 shows each task along with its period for accomplishment. In the following subsections the discussion of tasks is ordered more by data source than by the date of task initiation shown in Figure 1. The original (May 1990) task enumeration appearing

in Figure 1 is given here in parentheses.

The TACNEPH effort requires intensive computing facility resources to handle the large amounts of multisensor, multipplatform satellite data as well as the development of software needed to process and analyze that data. Software development is performed mainly on the PL / GPAS Air Force Interactive Meteorological System (AIMS), an integrated computer system of distributed general-purpose VAX and Encore processors, Adage imaging computers, VAX-based monochrome and color workstations, SPARC-II, Macintosh, and IBM PS/2 workstations. AIMS has been developed specifically to support research in environmental satellite data processing. Real-time direct read-out satellite data are acquired at the AIMS polar orbiter DMSP and NOAA groundstations and geostationary (GOES) and groundstation and stored in a 24-hour rotating on-line archive. Before being overwritten, digital data can be stored (archived) on optical disk or 4 mm tape. Global meteorological observations in the form of surface, upper air, and numerical gridded model guidance are received and decoded automatically via the National Weather Service "Family of Services" satellite link. A schematic diagram of the principal AIMS components is shown in Figure 2.

## 2.1 *Data Management Capabilities ( Task I )*

The first task initiated and still ongoing is that of the Mark IV-B database management which has the objective of developing AIMS software to meet TACNEPH requirements for handling and displaying many of the extensive sensor and supporting databases available on the Mark-IVB. TACNEPH Data Base (TDB) software supports management of most (e.g., no SSM/T-2) polar-orbiting satellite sensor data and corresponding ephemeris such as earth locations, solar zenith and sun-satellite azimuth angles, times, and calibration. Also included are image processing functionalities (in multi-projection formats) and unpacking algorithms for AVYRR data tapes in the NOAA / NESDIS Level 1 B format. TDB software also manages data from the real-time DMSP and NOAA ingest groundstations that are a part of AIMS. TDB provides both an interactive and FORTRAN-callable interface to support a wide variety of TACNEPH data users. Deliverables for this task include software documentation, a software design report, and VAX FORTRAN source code, all of which will be of potential use to the upcoming technology transition (T<sup>2</sup>) effort by way of providing flow-chart design and algorithm descriptions from which operational software can be developed.

## *2.2 SSM/I Surface Temperature Algorithm Evaluation ( Task 2 )*

Under this task the pre-existing algorithm currently used by the Real-Time Nephanalysis (RTNEPH; Hamill et al., 1992) that estimates surface skin temperatures using data from the DMSP microwave imager, the SSM/I, is to be incorporated into TACNEPH, and its subsequent effect on cloud analysis accuracy is to be determined. The technical approach will consist of validation of SSM/I-derived skin temperatures against OLS-derived clear-column estimates. Deliverables for this task include software documentation and design reports along with AIMS VAX FORTRAN source code. A scientific report is also required.

## *2.3 SSM/I Cloud Amount Algorithm Evaluation (Task3)*

Pre-existing algorithms that estimate cloud amount using SSM/I data are again to be incorporated into TACNEPH under this task and the resulting effect on cloud analysis accuracy will be determined. Work on this task is not scheduled to start until April 1993. Deliverables for this task include software documentation and design reports along with AIMS VAX FORTRAN source code. A scientific report is also required.

## *2.4 Development of OLS and AVHRR Cloud Algorithms ( Task 4 )*

The objective of the cloud algorithm task, the largest and most important task, is to develop single channel and multispectral cloud detection and analysis techniques that provide the best possible cloud retrievals under dynamic data availability constraints. The amount of NOAA and DMSP information can range from one to five channels of sensor data at any one time, depending on region of interest, satellite sensor, and time of day. Thus the cloud algorithms have been designed to dynamically adjust to changes in amount, type, and coverage of data. Single-channel and multispectral algorithms have been developed for visible-only, infrared-only, and multispectral data mix conditions.

TACNEPH cloud algorithm development initially started with the global Real-Time Nephanalysis (RTNEPH) model which has been in continuous operation at AFGWC (along with its predecessor, the 3DNEPH) for over 21 years and which is available in a research-grade form on the AIMS computing facility. While the fundamental requirement to operationally analyze satellite data to obtain cloud information is the same for both models, TACNEPH requirements deviate from those of the RTNEPH in

a number of areas. Among the more important differences are the regional vs. global nature of the models, the TACNEPH requirement to exploit multisensor data sources and to operate without non-satellite supporting databases, and the computational hosting environments under which each model must operate.

Three levels of cloud algorithms have been developed: a single-channel infrared (IR), a bi-spectral visible-IR, and daytime and nighttime versions of a multispectral cloud algorithm. The single IR channel algorithm is a statistical threshold type, comprised of three basic steps: 1) a threshold cloud / no-cloud decision, 2) a cluster layer analysis, and 3) a partially-cloudy-pixel analysis. The threshold step is actually a dual threshold approach that defines cut levels for completely cloudy and completely clear pixels. Sensor observations that lie between these values are treated as containing sub-pixel resolution clouds or cloud edges (see Gustafson and d'Entremont, 1992, in Appendix A). The layer step is the one used by the RTNEPH (d'Entremont et al., 1989). The partial cloud step computes the contribution of partly cloudy pixels to the total fractional amount using the technique applied in spatial coherence studies (Coakley and Bretherton, 1982). A flow chart of the single-channel technique is shown in Figure 3.

The two-channel algorithm, developed primarily for OLS visible-IR data, is analogous to the single-channel algorithm except that the cutoff threshold:: and subsequent data analysis are performed in two dimensions, as illustrated by Figure 4. In addition to the totally cloudy pixels, the contribution  $A_{pc}$  to total cloud cover of the partly cloudy pixels is given by

$$A_{pc} = 0.5 [ (R - R_{clr}) / (R_{cld} - R_{clr}) + (T - T_{clr}) / (T_{cld} - T_{clr}) ]$$

where R and T are the measured reflectance and brightness temperature values respectively, of the partially filled pixel, and where all other variables are as defined in Figure 4.

TACNEPH multispectral algorithms have as their basis the cloud clearing algorithms of Saunders and Kriebel (1988). There are six separate cloud detection tests in the daytime (seven at night), in addition to dynamic pre-filters for snow and sun glint conditions. Each test is sensitive to a different cloud spectral property and, as such, a positive result for only a single test is sufficient to detect cloud. Figure 5 contains a flow chart of the major components of the TACNEPH multispectral cloud algorithm. For details on each individual test, reference is directed to Gustafson and

d'Entremont (1992).

Deliverables for this task include documented research-grade code (developed on and for AIMS) in addition to scientific technical reports on algorithm attributes and validation results, most of which will be appearing in the refereed journals or PL / GP technical reports.

### *2.5 Evaluation of Cloud Height Assignment Using SSM/T Data ( Task 5 )*

The objective of this task is to evaluate the effect of incorporating data from the DMSP microwave temperature sounder, the SSM/T, for determining cloud heights in the TACNEPH environment. Cloud height assignments using SSM/T data will be evaluated using conventional data. As seen in Figure 1, work on this task began in July 1992 with the development of a temperature retrieval program for AIMS. Deliverables for this task include software documentation and design reports along with AIMS VAX FORTRAN source code. A scientific report is also required.

### *2.6 Develop Cloud Base and Thickness Algorithms ( Task 6 )*

The objective of this task is to develop techniques that provide improved estimates (relative to the RTNEPH) of cloud base / thickness using data that are available in the TACNEPH environment. Although their availability may be limited, techniques that incorporate surface observations of cloud cover will be considered as well. Techniques to be explored include statistical, direct-measurement, and remote-sensing based algorithms that principally exploit daytime cloud optical properties in terms of multispectral cloud reflectivities. Such reflectivities include measurements from DMSP OLS-L and NOAA AVHRR visible, near-IR, and mid-wave IR sensors (0.63, 0.86, and 3.7  $\mu\text{m}$ , respectively). Arrangements are being made to interact with scientists from NASA-Langley who are also actively working in this area (see for example Smith et al., 1992). Deliverables include software documentation and design reports along with AIMS VAX FORTRAN source code. A scientific report is also required.

### *2.7 Quality Control and Tuning ( Task 7 )*

The objective of the quality control task is to investigate and develop improved methods of TACNEPH cloud product visualization techniques and to provide for determining cloud analysis quality in ways that minimize manpower requirements in the Mark-IVB environment. PL / GPAS has over ten years of experience with



visualization display techniques that have proven invaluable in RTNEPH algorithm transition studies at the Geophysics Directorate (Bunting et al., 1983; d'Entremont et al., 1987; d'Entremont et al., 1989) and in operational, real-time applications of image display techniques at AFGWC and the German Military Geophysics Office in Traben-Trarbach, Germany (Klaes et al., 1992). This experience will be applied in development of TACNEPH visualization procedures. Work on this task is not scheduled to begin until FY93. Deliverables for this task include software documentation and design reports as well as AIMS VAX FORTRAN source code,

## 2.8 Process Conventional Cloud Observations (Task 8)

The objective of this task is to assimilate any available conventional observations of cloud cover into the TACNEPH cloud analysis product, with particular emphasis on improving the detection of low clouds and specifying cloud base and thickness. However, unlike the RTNEPH which merges independent satellite-only and conventional-only analyses of clouds, the TACNEPH approach will consist of analyzing satellite data with the *a priori* knowledge of surface-based observations of clouds. By using the two types of data in conjunction with each other, discontinuities will be minimized (or even eliminated) of cloud amounts and/or altitudes merged (forced) into the satellite analysis as a consequence of ground observations. Work on this task is scheduled to begin in October 1992. Deliverables for this task include documented research-grade code (developed on and for AIMS) in addition to scientific/technical reports on conventional algorithm attributes and validation results.

## 2.9 TACNEPH Computer Program (Task 9)

TACNEPH computer program development and maintenance is a task that is ongoing throughout nearly the entire TACNEPH project period. "TACNEPH computer program" means the AIMS research-grade software that performs as an algorithm testbed and whose design will serve as a potential Mark-IVB operation algorithm. The principle design philosophy of the TACNEPH computer code is such that I/O and cloud algorithm analysis functions are independent, modular routines that can be maintained separately but that operate together to perform analyses based on differing levels of satellite data availability. Enforcement of this standard is an AER responsibility that is monitored periodically by GPAS programmers. Deliverables for this task include software documentation and design reports as well as AIMS VAX

FORTTRAN source code.

### 3. Algorithm Validation

The candidate algorithms were developed and tested using case study data sets that were collected to represent the globally varying conditions under which TACNEPH is expected to operate. Climatological and geographic ranges include the tropics; low-latitude desert; mid-latitude vegetated land and ocean; and polar surface conditions of land, water, and ice. For each scene a time series of 8-14 days of data have been obtained for summer and winter. Interactive display techniques have been developed that depict algorithm results as color-coded overlays on the original satellite data. In this form the quality and accuracy of the TACNEPH cloud analysis is easily discernable, and especially helpful in identifying problem cases of low clouds and thin cirrus and inaccuracies arising in areas of changing topographic conditions such as coastlines.

In addition, AVHRR data obtained locally by the AIMS groundstation are being processed in near real-time by the multispectral TACNEPH algorithm. Resulting cloud analyses are being manually inspected by a trained image analyst for accuracy and to help identify systematic problem areas of the cloud analysis itself. The areas of cloud analysis are Hudson Bay, New England; the Gulf Stream region south of New England and east of New Jersey and Delaware, and Florida, all of which are within the area of coverage of the NOAA polar groundstation at Hanscom AFB.

Results are encouraging for both single and multispectral algorithms. Multispectral AVHRR algorithms in particular show an improved capability relative to the RTNEPH I to detect low clouds and fog. Analysis of cirrus, especially thin cirrus as well as snow-cloud discrimination in the polar regions, are also improved. The algorithm also provides information on cloud type, phase, and layer altitudes. Results from the two-channel visible-IR algorithm have been evaluated using AVHRR channels 2 and 4 as surrogate OLS-L and T channels. Problem areas that are being investigated include incorrect modeling of background reflectance over desert and ocean; snow-cloud discrimination under conditions of low solar illumination; clear-cloud discrimination in regions of coastlines; and the accuracy of supporting databases such as geography type and surface skin temperature climatologies and corrections.

A separate algorithm validation set will be assembled specifically for TACNEPH

algorithm validation purposes and to insure continuity following TACNEPH T<sup>2</sup> activities. Air Weather Service (AWS) representatives from the SPO have asked to participate in the specification of the validation data set and have also agreed to assist in the acquisition of high-resolution sensor data from OLS and AVHRR. PL and AER welcome SPO suggestions on the selection of suitable test scenes and in the designing of the validation procedure.

*→ have they been tested in Regions  
5 similar to those that the sites it will be @*

#### 4. Present Program Status

Figure 1 gives timelines and progress for the nine tasks in the TACNEPH development undertaken by GPAS and the major support contractor, Atmospheric and Environmental Research, Inc. (AER). The following tasks were ongoing as of August 1992: Task 1, database management, including real-time data ingest; Task 2, SSM/I surface temperatures; Task 4, OLS and AVHRR algorithms; Task 5, SSM/T cloud heights; and Task 9, TACNEPH computer program development. AER has completed three data base subtasks and provided software design reports for them. Task 6, cloud base and thickness algorithms, will start September 1992. Tasks 3, 7, and 8 are scheduled to start later.

Also completed under Task 1, satellite ground stations now provide real-time DMSP and NOAA data ingest which is used in direct support of TACNEPH. To date, the NOAA ingest has provided the cloud algorithm quality assessment data sets for the four geographic areas referred to in Section 3. The real-time DMSP ingest has only recently become available, and will be used directly in the validation of the single-channel and two-channel OLS algorithms and in the utilization of near-infrared algorithms.

Under Task 4, algorithms have been designed to identify clear, partly cloudy and cloudy samples for one, two, and multi-channel data available from OLS and AVHRR. Task 4 also calls for surface temperatures estimates from the satellites for clear areas. The surface temperatures are needed as input to Tactical Decision Aids users and also improve the cloud detection. All of the TACNEPH cloud detection algorithms use a surface temperature test at some stage for cloud detection. The sensed surface temperatures allow automatic updating of corrections to the surface temperature climatology to reduce errors associated with the climatology. Similar progress has been made in generating background brightness fields for visual and near-infrared channels.

In addition to the algorithm development, government personnel have assisted in evaluating the capabilities of the Mark IV-B and in preparing a Meteorological User's Guide for it. Moreover, information on TACNEPH algorithms and cloud display capabilities has been provided to DMSP Block 6 efforts and to the AFGWC for planning and transition purposes.

## 5. Technology Transition Issues

Details of transitioning the science and technology contained in the cloud detection algorithms developed at GPAS have never been specified. Uncertainties as to final host hardware and overall size and complexity of TACNEPH algorithms and support databases have precluded detailing the process. Now that these hardware and algorithm constraints are known, the  $T^2$  process must begin.

Technology transition in the sense of construction and implementation of operational code is considered by GPAS and its in-house contractor to be supplemental to and distinguished from the TACNEPH program outlined in Sections 1 and 2. The overall GPAS responsibility in TACNEPH is to incorporate state-of-the-technology cloud detection and specification techniques into new algorithms and implement them on AIMS as a research-grade code for the purpose of proof-of-concept, technique demonstration, and validation. The distinctions between research and development, vis-a-vis operational implementation of TACNEPH are indicated in tabular form below.

### TACNEPH Implementation Issues

Research <i>and Development</i>	<i>Operational</i>
1. Research (Changeable) Code	Operational (Robust) Code
2. Case-Study Databases	Continuous, Regional Databases
3. Post-Facto, Episodic Operation	Real-Time Operation
4. Augmented AIMS Hardware	Mark IV-B Hardware
5. Case-Study Vehicle	Prime Use - Operational Support

The  $T^2$  elements that GPAS will provide are documentation, reporting, and validation data set maintenance. Software per se is not a deliverable item. All

software developed for TACNEPH is in the form of research-grade code and can only be executed on AIMS. However, it is anticipated that the source code listings will be useful instructional aids for programmers tasked with the operational implementation of the algorithms.

Although GPAS is not constructing or implementing the operational code, the software transition process is being assisted by adhering to stringent documentation and reporting standards. Documentation means plain-language descriptions and supporting diagrams indicating for each algorithm 1) its function; 2) the control sequence; 3) input / output specifications; 4) supporting database structure, access, utilization, and update; and 5) its integration into the overall TACNEPH program.

The reporting  $T^2$  element includes written technical reports (detailed in Section 2), periodic reviews, and algorithm demonstrations. As part of the reporting element, TACNEPH architecture documentation will be prepared for each scientific task as it proceeds, is completed, and is integrated into the overall TACNEPH program. These reports, along with reviews and demonstrations, will be constructed with the transition process in mind and are available to the sponsor and other concerned agents,

The third  $T^2$  element of TACNEPH is the assembling and maintenance of standard validation data sets for the four test areas employed in the research effort (refer to Section 3). These data sets will be used during the R&D effort to assess the effectiveness of incremental improvements and will be used to insure that the final operational cloud analysis model is functioning correctly.

Neither GPAS nor its primary in-house contractor has the experience in producing operational code that is required to successfully  $T^2$  the TACNEPH algorithms to the Mark IV-B environment. It is therefore recommended that such an agent soon be recruited and become involved with the TACNEPH program at GPAS.

## 6. Recent TACNEPH In-House and **Primary Contractor Publications**

### *6.1 Presentations at Cloud Impacts on DoD Operations and Systems (CIDOS-91), July 1991, Los Angeles CA.*

Gustafson, Gary B., Jean-Luc Moncet, Ronald G. Isaacs, Robert P. d'Entremont, James T. Bunting, and Michael K. Griffin, 1991: TACNEPH Single Channel and Multispectral Cloud Algorithm Development. Proc. CIDOS-91 July 1991.

Los Angeles, CA.

Isaacs, Ronald G., and Gary B. Gustafson, 1991: Tactical Nephanalysis (TACNEPH) Program Overview. Proc. CIDOS-91, July 1991, Los Angeles, CA.

Thomason, Larry W., and Robert P. d'Entremont (Presenter), 1991: Simulation of Color-Composite Imagery on 8-Bit Display Devices. Proc. CIDOS-91, July 1991, Los Angeles, CA.

#### 6.2 *Sixth Conference on Satellite Meteorology and Oceanography, Atlanta GA, January 7 1992*

d'Entremont, Robert P., Donald P. Wylie, J. William Snow, Michael K. Griffin, and James T. Bunting, 1992: Retrieval of Cirrus Radiative and Spatial Properties Using independent Satellite Data Analysis Techniques. Proc. Sixth Conf. on Satellite Meteorology and Oceanography, 5-10 January 1992, Atlanta GA, Amer. Meteor. Soc., 17 - 20.

Griffin, Michael K., Robert P. d'Entremont, and Larry W. Thomason, 1992: The Simulation of Multispectral Composite Satellite Imagery on 8-Bit Color Workstations. Proc. Sixth Conf. on Satellite Meteorology and Oceanography, 5-10 January 1992, Atlanta GA, Amer. Meteor. Soc., J92 - J95.

Gustafson, Gary B., and Robert P. d'Entremont, 1992: Single-Channel and Multispectral Cloud Algorithm Development for TACNEPH. Proc. Sixth Conf. on Satellite Meteorology and Oceanography, 5-10 January 1992, Atlanta GA, Amer. Meteor. Soc., 13 - 16.

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#### 6.3 *Scientific Reports*

d'Entremont, Robert P., 1992: Colocation of AVHRR and HIRS Pixel Fields of View for Multispectral, Multisensor Cirrus Analysis. Phillips Laboratory, J Geophysics

Klaes, K. Dieter, Robert P. d'Entremont, and Larry W. Thomason, 1992: Applying an 8-Bit Multispectral Color-Composite Image Simulation Technique to Operational Real-Time AVHRR Data. *Bull. Amer. Meteor. Soc.*, 73, 766 - 772.

Thomason, Larry W., and Robert P. d'Entremont, 1992: Full-Color Composite Imagery for 8-Bit Display Devices. Submitted *Int. Journ. Remote Sensing*, March 1992.

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d'Entremont, Robert P., and Larry W. Thomason, and James T. Bunting, 1987: Color-Composite Image Processing for Multispectral Meteorological Satellite Data. Proc. SPIE Conf. on Digital Image Processing and Visual Communications Technologies in Meteorology, 27-28 October, Cambridge MA, *SPIE*, 96 - 106.

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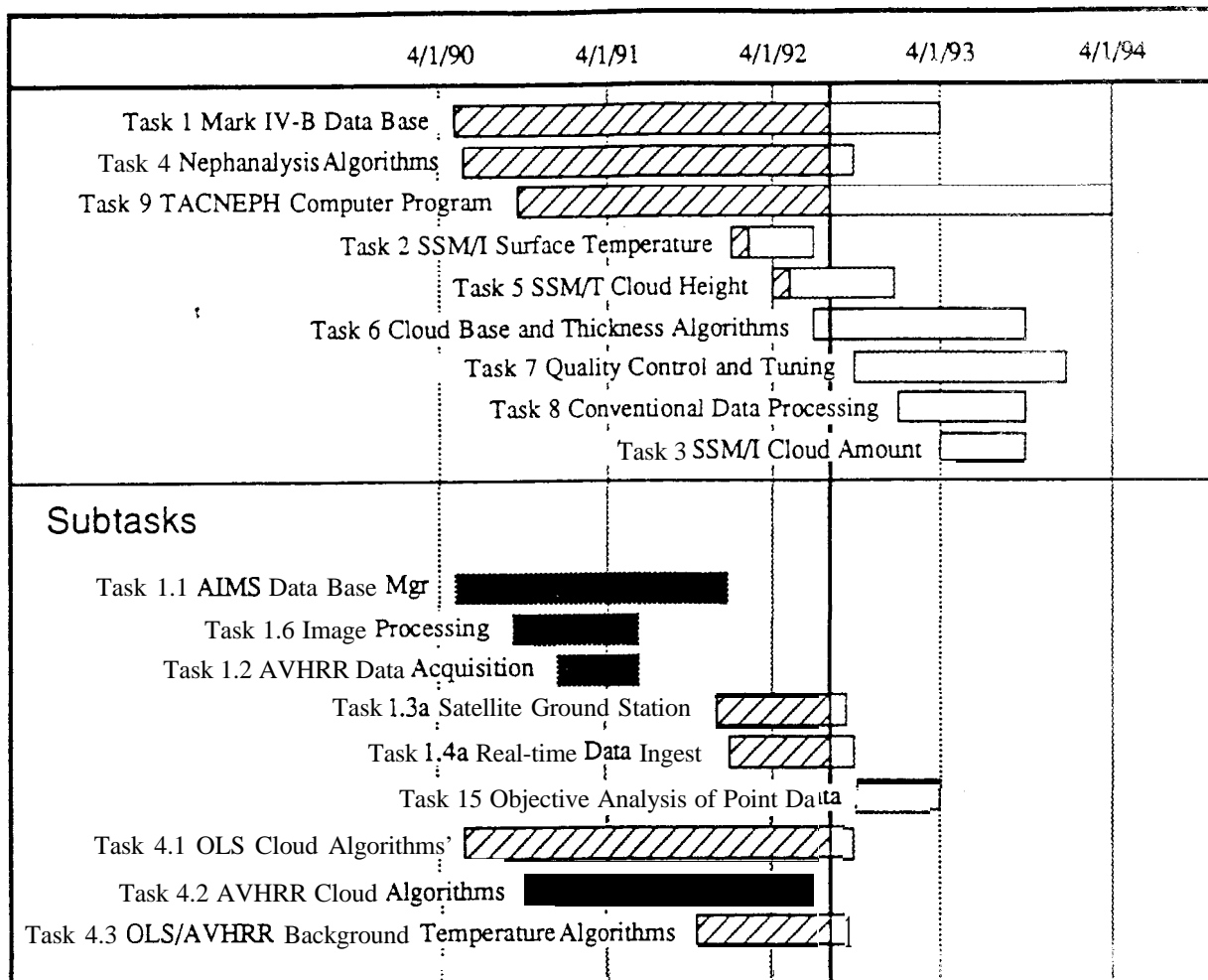
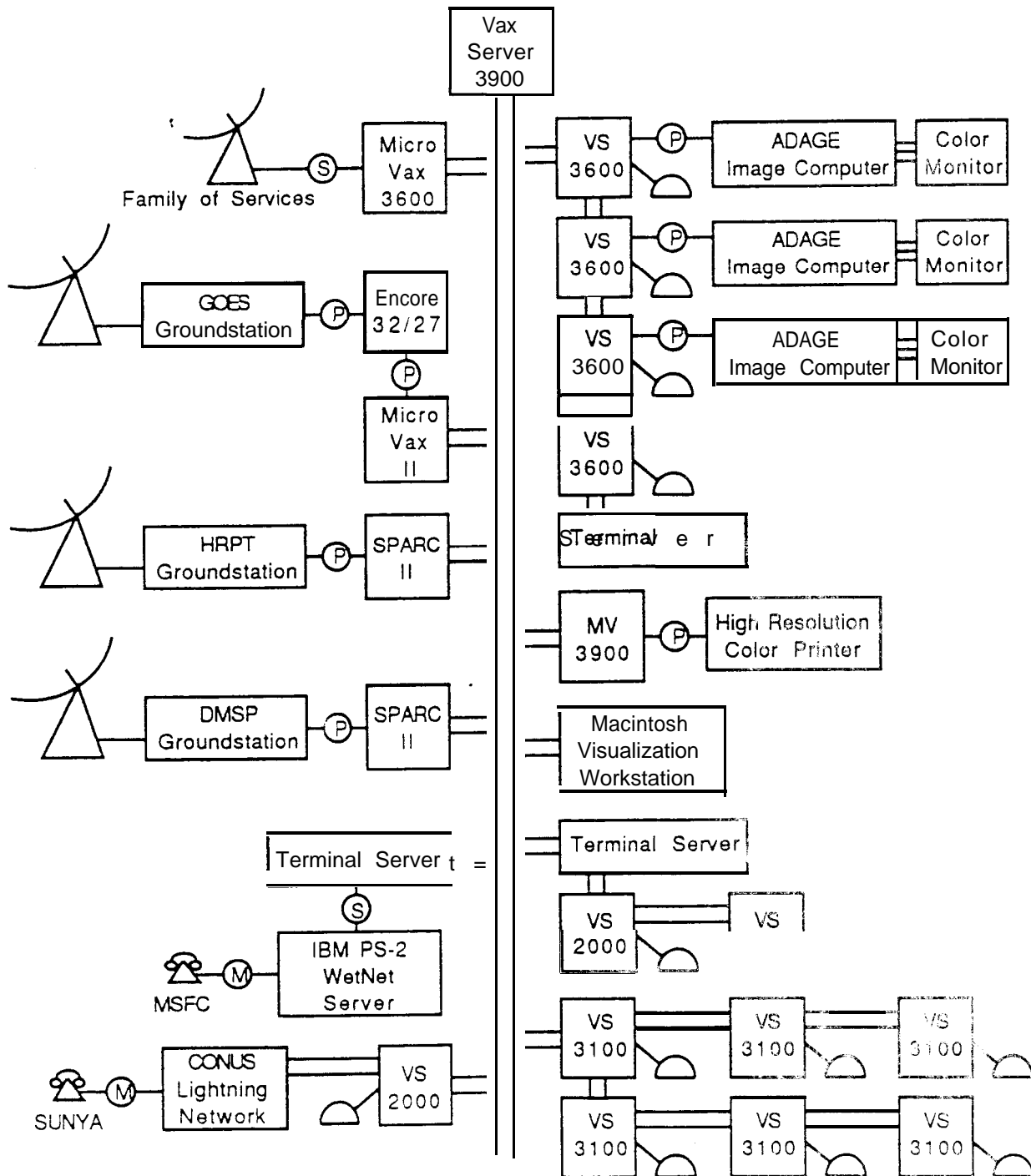


Figure 1. TACNEPH Tasks

## Air Force Interactive Meteorological System (AIMS)



**Figure 2. AIMS System Configuration**

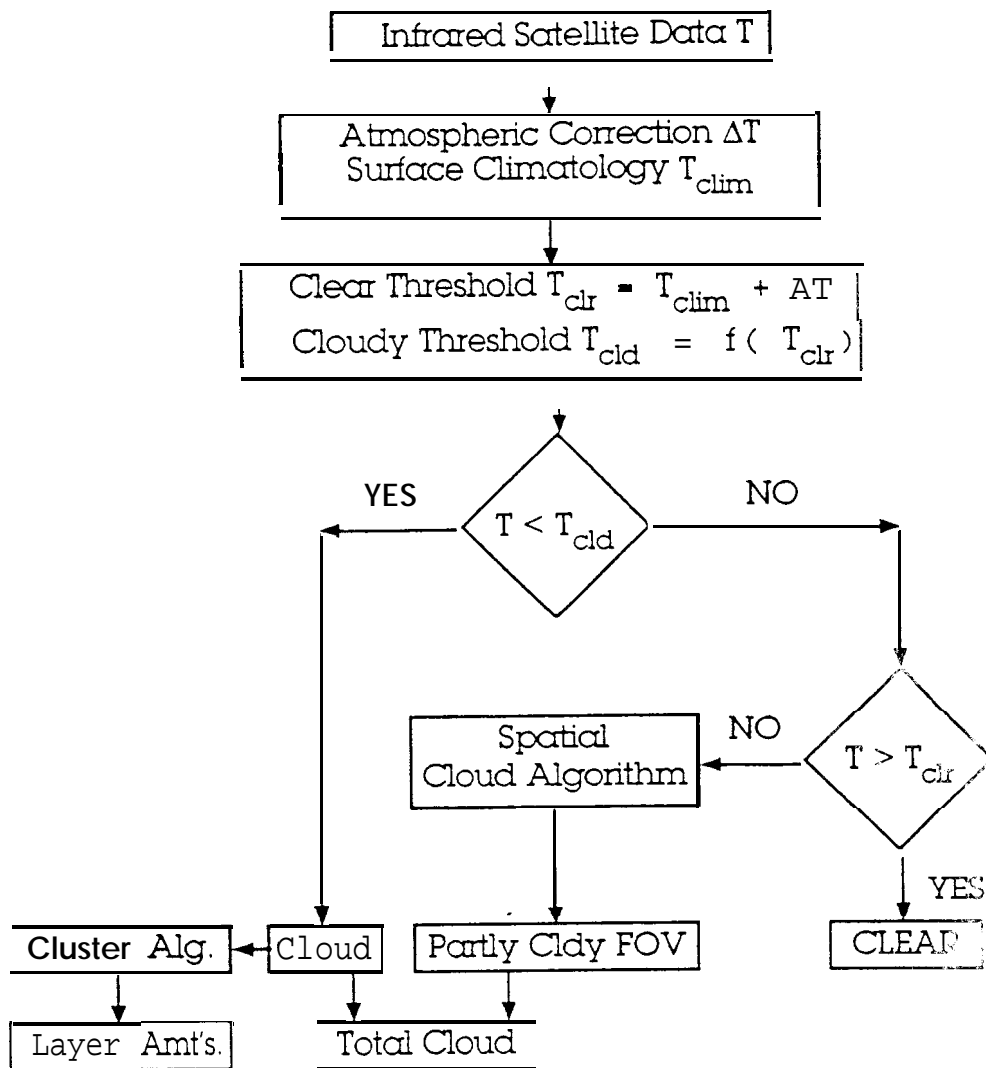


Figure 3. TACNEPH Single-Channel Infrared Algorithm

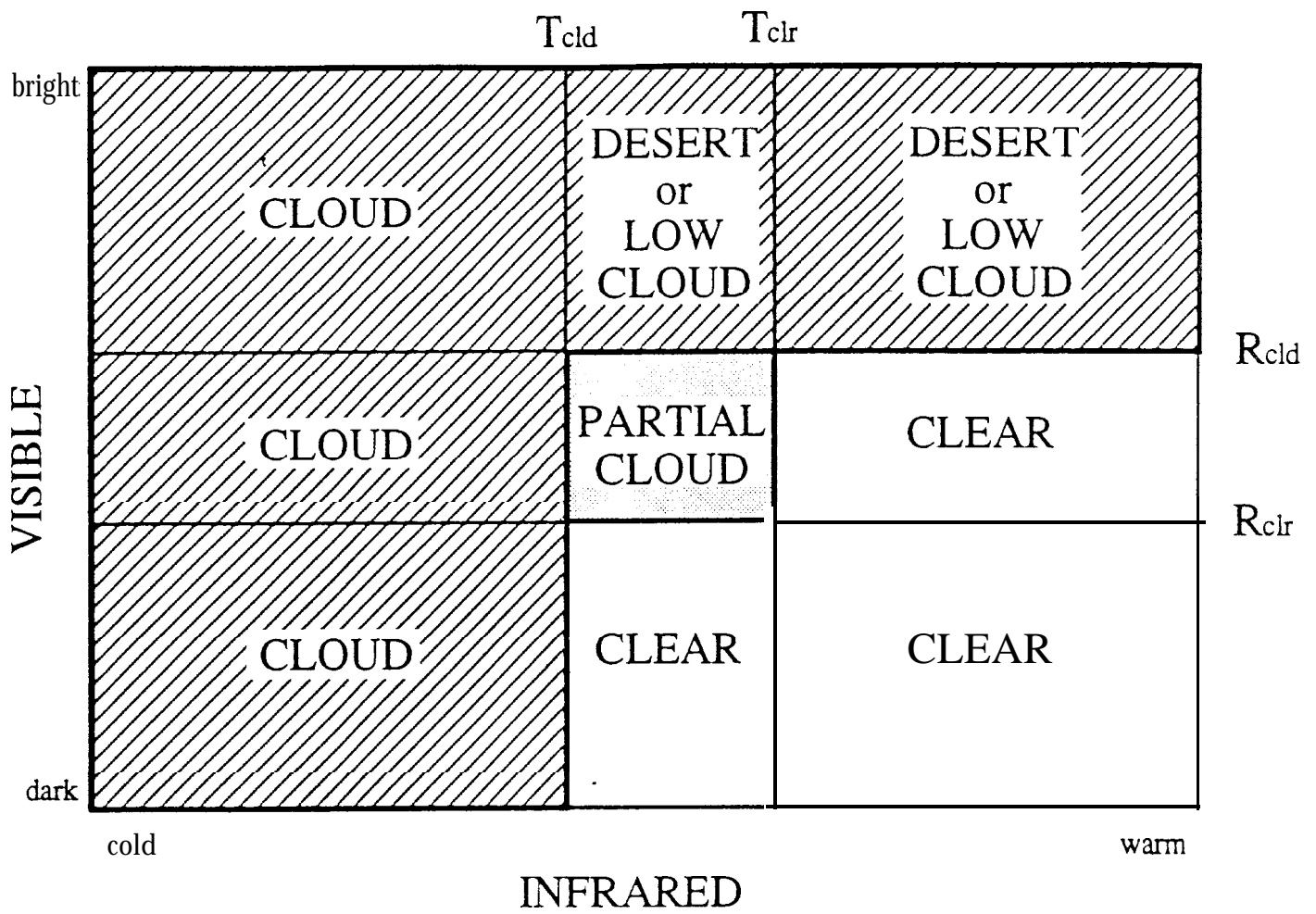


Figure 4. TACNEPH Two-Channel Algorithm Classification Regions

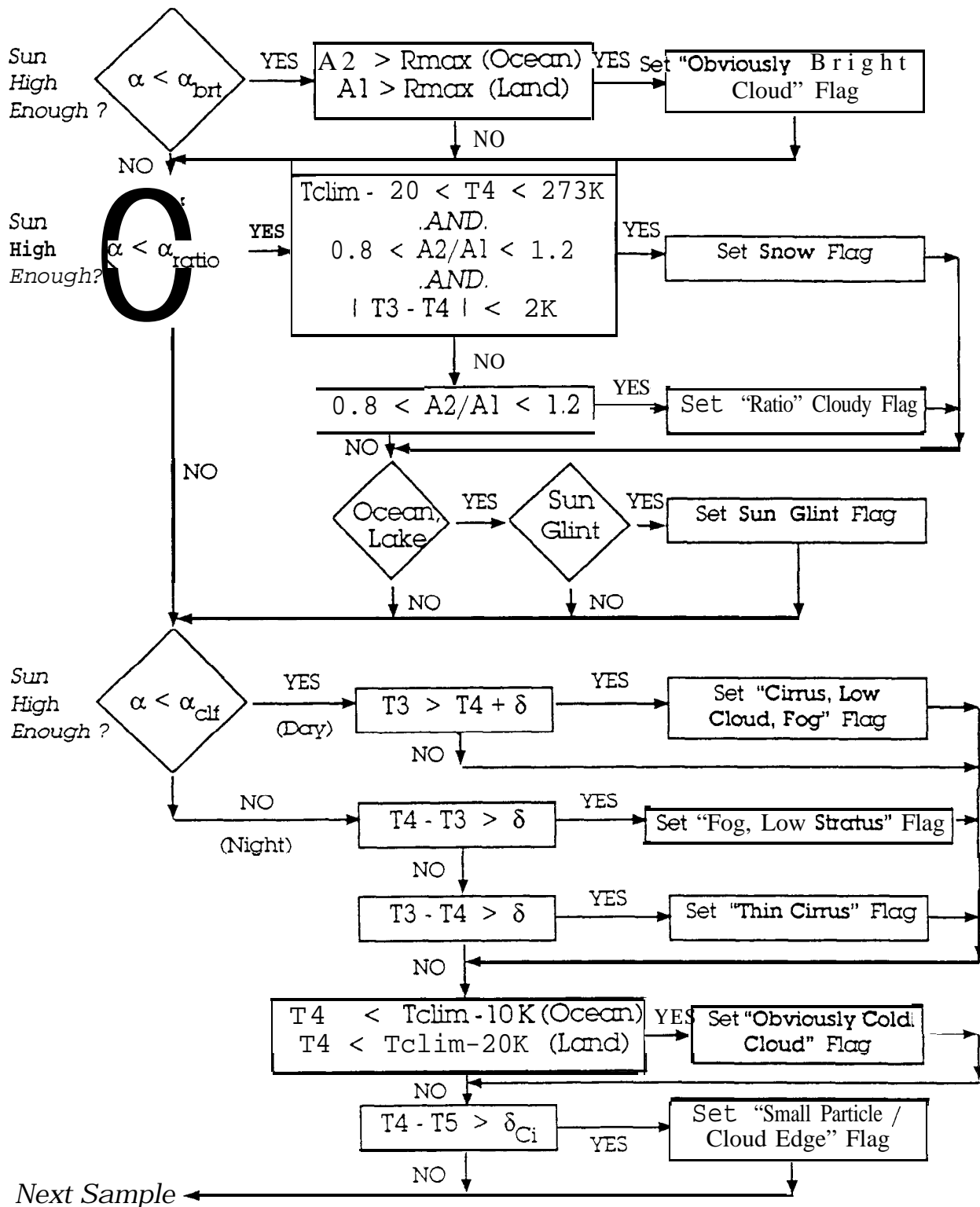


Figure 5. TACNEPH Multispectral AVHRR Algorithm. "a" Denotes Scene Solar Elevation Angle; A1, A2 Are Chs. 1, 2 Albedos; T3, T4, T5 Are Chs. 3, 4, 5 Brightness Temperatures.

## 8. Appendix A

## Appendix A.

### SINGLE CHANNEL AND MULTISPECTRAL CLOUD ALGORITHM DEVELOPMENT FOR TACNEPH

Gary B. Gustafson

Atmospheric and Environmental Research, Inc.  
Cambridge, MA 02139

Robert P. d'Entremont

Geophysics Directorate, Phillips Laboratory (AFSC)  
Hanscom AFB, MA 01731

#### 1. INTRODUCTION

TACNEPH is an ongoing Air Force sponsored program to develop a **relocatable** regional cloud analysis model for **operational** use at **transportable** satellite ground receiving stations. Key model **requirements** are the ability to assimilate data from both military and civilian polar orbiting satellites in **real** time and to **analyze** sensor data for the purpose of developing **gridded** fields of fractional cloud amount and height. The TACNEPH heritage lies in the global RTNEPH model which the Air Force has been operating continuously (along with its predecessor the 3DNEPH) for over 20 years. However, while the fundamental **requirement** to operationally **analyze** satellite sensor data to obtain cloud information is the same for both models, TACNEPH requirements depart from RTNEPH capabilities in a **number** of areas. Important **differences are the regional vs. global nature of the models, the TACNEPH requirements to exploit multiple sensor data sources and to operate in the absence of supporting databases from non-satellite sources, and the environments in which the two models operate.**

Multiple **nephanalysis** algorithms **are** necessary to satisfy the TACNEPH requirements. To **date** four prototype algorithms **have been** developed; two **statistical/threshold** techniques and daytime and **nighttime** versions of a **multispectral decision tree type** of algorithm. Algorithm **testing** and validation is a large part of the program to ensure that candidate techniques **are** robust enough to satisfy **operational requirements for the wide range of conditions that the model could potentially be employed over.** Future work will include development of **sensor based surface radiative skin temperature and reflectance models, application of microwave sensor data to background characterization and cloud height assignments, integration of conventional cloud observational data into the satellite based nephanalysis, and interactive techniques for quality control and validation.**

#### 2. PROGRAM OVERVIEW

TACNEPH is a four year research and development program being carried out at the Phillips Laboratory Geophysics Directorate. The principal objective of the program is development and validation of satellite nephanalysis algorithms for cloud detection and estimation of fractional cover and altitude. Corollary efforts include development and/or validation of objective algorithms capable of deriving additional cloud properties including type, base, and thickness. All algorithms are constrained to operate using only the data and computing resources available in a **transportable satellite**

receiving station. This implies that conventional data **may not** always be available and that algorithms must **be** designed to dynamically adjust to changes in availability of supporting data and in **coverage, quality, and available sensor channels of satellite data.** In particular TACNEPH algorithms **are required to:**

- 1) exploit multiple sensor data sources including DMSP OLS, SSM/I, SSM/T and all five NOAA AVHRR channels;
- 2) operate **in** the absence of any dynamic **data source** other than direct satellite **sensor transmissions;**
- 3) automatically **select** the optimal **processing algorithm** in response to changes in data **availability or quality;**
- 4) provide techniques to customize the **analysis methodology** basal on **location parameters** that characterize the radiative properties of a **particular region; and**
- 5) provide quality control **information** along with analysis results to allow **operational users in the field** to assess the quality and accuracy of the derived cloud **properties.**

To address these requirements eight functional tasks have been identified to: 1) develop sensor and supporting database **capabilities** including data acquisition, database **management, Earth location and spatial transformation, image processing, to display;** 2) develop OLS and AVHRR **nephanalysis algorithms;** 3) develop OLS and AVHRR clear scene **skin temperature algorithms;** 4) evaluate existing SSM/I surface temperature algorithms **for estimation of skin temperature;** 5) evaluate cloud height assignment using SSM/T-derived **temperature profiles;** 6) develop cloud base and thickness algorithms; 7) develop procedures for quality control and interactive manipulation of analysis **results; and 8) integrate** conventional cloud observations with satellite derived **analyses.**

#### 3. CLOUD ALGORITHMS

The approach to cloud algorithm development is illustrated in Figure 1 wherein multiple algorithms exist to satisfy the **external constraints** imposed by the data mix. As indicated by the arrows surrounding the diagram, it is assumed that the **baseline capability (level 1)** has the highest reliance on locally available and stored databases (which may require periodic updating to insure timeliness) and the least reliance on satellite sensor data. As contingencies develop that decrease

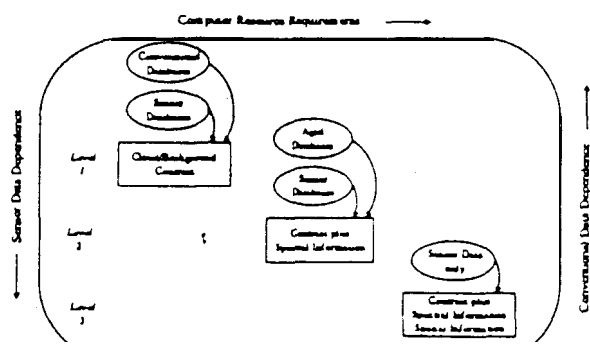


Fig. 1. TACNEPH conceptual approach.

the reliability of stored databases the analysis program will switch to higher levels of processing that are less dependent on supporting data. An important feature of this multilevel approach is the capability to perform simultaneous algorithm co-calibration in the field. The inherent algorithm redundancy is exploited to calibrate one algorithm against another during conditions of full data availability. This provides output statistics from the analysis algorithms that will be used to assign confidence levels to results obtained later during non-optimal data-limited conditions.

Algorithms have been developed to accommodate the range of imager data expected from the OLS and AVHRR instruments. Two statistical threshold type algorithms have been designed to operate using a single infrared thermal window channel alone or in combination with a visible or near-IR channel (i.e., OLS-T and OLS-L; AVHRR channels 1 or 2 and 4 or 5). Daytime and nighttime multispectral algorithms use all available channels from the AVHRR simultaneously. The multispectral approach uses a decision tree structure to classify individual scene features (e.g., low cloud, cirrus, snow, sun glint) separately through evaluation of a selected set of spectral signatures at each branch. For this application spectral signatures are taken to be combinations of channel ratios, differences and absolute magnitudes. This approach has been used successfully in operational cloud clearing applications (e.g. Saunders and Kriebel, 1988; Karlsson and Liljas, 1990). However, for TACNEPH it is being modified to operate as a cloud detection program. Information on cloud type and cloud optical properties is produced as a by-product of the multispectral cloud detection algorithms.

### 3.1 Single Channel

The single IR channel algorithm is a three step procedure: 1) a threshold cloud detection test, 2) a cluster/layer analysis, and 3) a partial cloud analysis. The objective of this scheme is to identify cloud-filled, cloud-free and partially cloudy pixels within the scene and to determine a representative temperature associated with each cloud layer and cloud free area. This information is then used to compute the required parameters for each layer, namely fractional amount, cloud top temperature, and altitude.

In general, a threshold approach is well suited for a one or two channel technique since any uncertainties in the data, including sensor calibration, clear scene characteristics, and atmospheric transmission, can be accounted for in a single threshold value. The TACNEPH threshold test is designed to estimate the combination of completely cloud filled pixels to the total amount. Most threshold based cloud algorithms use a single cutoff value to discriminate cloud filled from cloud free pixels. However, as illustrated in Figure 2a, this will produce errors in fractional amount due to incorrect classification of

partially filled FOVs. Additionally, cloud boundaries tend to be amorphous and the actual definition of where they occur generally depends on the application. The TACNEPH algorithm attempts to minimize these problems through a dual threshold approach wherein separate cutoff values are identified for completely cloudy and completely clear pixels (Figure 2b). Data points that lie between the two cutoff values are treated as partially filled (i.e. contain a cloud edge). Image pixels classified as completely cloud filled by the threshold test are subjected to a clustering algorithm that provides a brightness temperature analysis of a layered cloud system (d'Entremont et al., 1989). Up to four floating cloud layers are identified and representative temperatures are assigned to each layer in order to anchor them in a temperature height profile. The third and final step is an estimation of the contribution of partially filled FOVs to the total cloud amount. This step is adapted from the spatial coherence technique developed by Coakley and Bretherton (1984) in which fractional cover is given by an energy balance equation:

$$A_c = \frac{(I - I_{clr})}{(I_{cld} - I_{clr})}$$

where  $A_c$  is effective cloud cover,  $I$  is measured scene radiance,  $I_{cld}$  is representative cloud radiance, and  $I_{clr}$  is representative clear scene radiance. The TACNEPH algorithm departs from the spatial coherence approach in two ways: 1) only pixels that have been previously determined to be partially filled are used in the calculation; and 2)  $I_{clr}$  and  $I_{cld}$  are obtained from the mean radiance of the clear and lowest cloud layer pixels, respectively, as determined by the threshold analysis.

### 3.2 Two Channel

The second statistical/threshold algorithm is a two channel approach developed primarily for the OLS. This algorithm is similar to the single channel approach described above, however, a two dimensional threshold technique is used to classify the clear, cloud filled, and partially cloudy pixels. Conceptually the two channel approach is straightforward: data from both a visible and infrared sensor channels

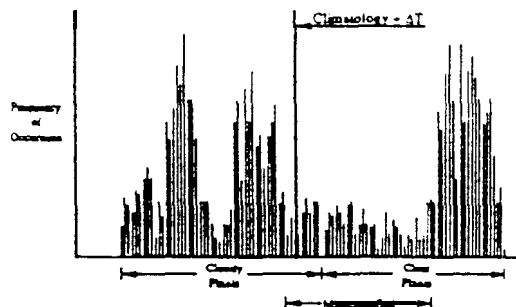


Fig. 2a. Single threshold analysis illustrating misclassified partially filled pixels.

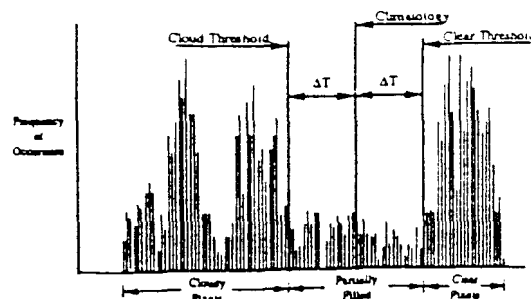


Fig. 2b. Dual threshold analysis illustrating classification of partially filled pixels.



are analyzed simultaneously using two sets of cutoff values, one in each dimension. Figure 3 illustrates how the two dimensional visible-IR space is divided into nine classification regions by the cutoff values. Infrared data that are colder than the IR cloud cutoff value ( $T_{cld}$  in the figure) are unambiguously classified as cloud over snow- and ice-free backgrounds. Data that are both warm and dark (i.e. below both  $T_{cld}$  and  $R_{cld}$  and either  $T_{clr}$  or  $R_{clr}$ ) are unambiguously classified as clear. Warm bright regions (i.e. exceed  $R_{cld}$  but below  $T_{cld}$ ) require an a priori clear scene classification to remove the ambiguity caused by the similarity in radiative signatures of backgrounds such as deserts and low cloud. Data points that fall between all four cutoff values are classified as partially cloud filled. Their contribution to total cloud amount is calculated geometrically; it is assumed to be proportional to the distance a data point lies from both clear cutoff values (i.e.  $R_{clr}$ ,  $T_{clr}$ ) in the space defined by the intersection of the four cutoff levels. The expression for the effective cloud cover  $A_c$  is:

$$A_c = \frac{1}{2} \left( \frac{T - T_{clr}}{T_{cld} - T_{clr}} + \frac{R - R_{clr}}{R_{cld} - R_{clr}} \right)$$

where R and T are the measured reflectance and brightness temperatures, respectively, of the partially filled data point and  $T_{clr}$ ,  $T_{cld}$ ,  $R_{clr}$ , and  $R_{cld}$  are the clear and cloud cutoff values for the infrared temperatures and visible reflectances.

### 3.3 Multispectral

TACNEPH multispectral algorithm work is based on the cloud clearing algorithms of Saunders and Kriebel (1988). Five separate cloud detection tests in a hierarchical structure are used to characterize the scene. In addition separate snow and sun glint tests pre-filter the data for problematic background conditions. Each test is applied in succession and a positive result for any one test is sufficient to detect cloud.

**Snow and Ice Tests:** Three conditions are required for the algorithm to detect snow. 1) The scene must be at or below freezing and still within 20 K of the climatological temperature; 2) the ratio of the near IR to visible reflectance values must be near unity since vegetated land surfaces tend to have ratios significantly greater than 1; and 3) since snow is relatively non-reflective at  $3.7 \mu m$  the magnitude of the channel 3 brightness temperature should be near that of channel 4. The suspicion of a snow background precludes the use of channels 1 and 2 from the cloud tests.

**Sun Glint Test:** Specular reflection off of water surfaces generally causes a false cloud signature to occur in tests which use channels 1, 2, or 3. Five attributes have been identified that are characteristic of glint conditions: 1) near IR reflectance is high; 2) channel differences between the visible and near IR

tend to be masked by the glint, hence the ratio of the two channels is near 1; 3) the combined emitted and reflected solar components measured at  $3.7 \mu m$  is large relative to the emitted-only long wave radiance resulting in a channel 3 brightness temperature much larger than channel 4; 4) the scene brightness temperature is high relative to the reference clear scene temperature; and 5) LWIR channel differences (channel 4-5) caused by small cloud or ice particles do not exist. Similar to the snow tests, a suspected sun glint region eliminates any tests that rely on a reflected solar signature (including tests that use channel 3).

**Visible Gross Cloud Test:** This test is a simple single threshold test designed to eliminate obvious cloud from further processing. Different cutoff levels are used over land and water backgrounds to account for the increased uncertainty in the clear scene estimates over land surfaces. Large thresholds are used to minimize the possibility of classifying an abnormally bright background surface as cloud.

**Near IR to Visible Ratio Test:** As discussed above, dark background surfaces often appear brighter at visible wavelengths than in the near IR due to increased atmospheric scattering at the shorter wavelengths. However, vegetated land surfaces tend to have a higher reflectance at the channel 1 bandpass than at channel 11, overwhelming the atmospheric scattering effect. Cloud tends to wipe out both of these clear scene signatures since cloud reflectance is approximately equal at both channel wavelengths and cloud tops generally lie above the layer of the atmosphere where most scattering occurs (d'Entremont et al., 1987). Therefore, in the absence of snow or sunglint channel 2/channel 1 ratios will be greater than 1 for most clear vegetated scenes, less than 1 for clear ocean, and near unity for cloud. Ambiguities occur over some desert and bare rock surfaces.

**Mid to Long Wave IR Tests:** During nighttime passes,  $3.7$  and  $11 \mu m$  channel differences are used to detect low clouds and fog. Water droplet clouds have  $3.7 \mu m$  emissivities ranging from 0.35-0.90, depending on droplet sizes and total cloud optical depth while land surface emissivities range around 0.90 (Hunt, 1973). This results in lower MWIR brightness temperatures relative to LWIR measurements of these clouds. To detect low cloud the nighttime algorithm tests for channel 4 brightness temperatures greater than channel 3 temperatures. In sunlit conditions liquid water clouds reflect as well as emit at  $3.7 \mu m$ . These clouds appear warmer at channel 3 than at the LWIR channels where then is only an emitted component. The daytime test exploits these channel differences through criteria that require a channel 3 brightness temperature greater than the channel 4 temperature. In both tests the channel differences must exceed an empirically derived threshold value that is defined regionally. Also the daytime test requires filters for sunglint, snow, and other reflective backgrounds.

**Split IR Window Test:** Channel differences between the two AVHRR LWIR channels (4 and 5) are used to detect optically thin cirrus and edges of thicker ice and liquid water clouds. Brightness temperature differences between these two channels exceed the amount expected for water vapor absorption and Planck functional dependence for these types of cloud. Inoue (1987) recognized that this difference was caused by differences in extinction of thin ice particle clouds between 11 and  $12 \mu m$ , with the greater extinction at  $12 \mu m$ . Prabhakara et al. (1988) extended this signature to include both liquid water and ice clouds when the droplet or particle size was smaller than the channel wavelength. Saunders and Kriebel (1988) developed a test to exploit these signatures through a look-up-table of expected clear scene channel differences due to preferential water vapor absorption at channel 5. To detect cloud the measured channel differences must exceed the table predicted value by an amount in excess of a preset threshold.

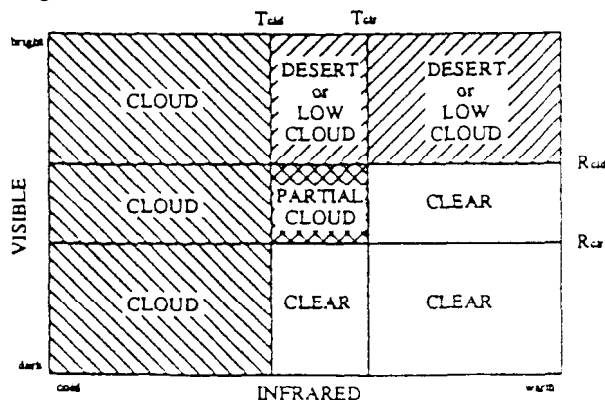


Fig. 3. Clear/cloud classification regions of the two channel algorithm.

#### 4. ALGORITHM VALIDATION

Candidate algorithms are being evaluated using case study data sets collected to represent the range of climatological and geographic conditions over which TACNEPH is expected to operate. Case study data include AVHRR imagery and climatological surface temperatures for four regions representing the tropics; low latitude desert; mid latitude vegetated land and ocean; and polar land, water, and ice backgrounds. For each case a minimum of six days of time-contiguous data have been collected for two seasons: summer and winter. Interactive software to display algorithm results as color coded synthetic imagery over top of original sensor data is used to manually evaluate algorithm results. This has proven to be an effective technique for analyzing nephelometer accuracy over different cloud types and backgrounds and for identifying problem areas in the cloud analysis itself.

Preliminary results are encouraging. Multispectral algorithms in particular show an improved capability relative to the RTNEPH to detect low cloud and fog over a variety of backgrounds. The visible to near IR and mid to long wave IR tests contribute most to low cloud detection. Cirrus detection using both the split IR window and mid to long wave IR tests is also improved. In daylight conditions the ice test provides excellent discrimination of sea ice from polar stratus. Analysis of individual test results also furnishes information on cloud properties such as type, phase, and relative layer height.

A number of problem areas have been identified, principally in the analysis of reflected solar radiation. Enhanced reflection from disturbed ocean surfaces well away from the expected specular point have caused spurious cloud signatures in the visible, near IR, and mid IR channels. Similarly, extreme variations in surface characteristics over desert regions (presumably caused by different surfaces such as sand and rock in close proximity), which are poorly resolved in background reflectance databases due to their highly anisotropic nature, often result in anomalous cloud detection. Highly reflective desert surfaces can also mask the reflected cloud signature in the mid IR channel due to sensor saturation. At high solar zenith angles discrimination of ice and low stratus becomes problematic due to the lack of sufficient reflected solar energy to satisfy the ice detection criteria. Finally, many of the tests require different threshold values over land vs. water or vegetated vs. barren backgrounds due to their different radiative characteristics. Poor resolution or granularity in supporting databases that identify the background classification can result in the appearance of persistent phantom clouds along the boundaries between adjacent background types. This phenomena can also occur whenever the thermal contrast between nearby background regions is too large to be resolved accurately by the surface temperature database. All of these problem areas are being investigated either through solutions that test for additional radiometric characteristics or through inferential criteria based on analysis of nearby pixels or regions.

#### 5. SUMMARY

A multiyear program is underway to develop a regional satellite cloud analysis model that can be adapted for any location on the Earth. The model is constrained to operate using only satellite sensor and stored databases although under some operating conditions conventional data may be available. To accommodate the variability in coverage, quality, and amount in the available data mix, multiple nephelometer algorithms are being developed and tested. To date two classes of algorithm have been investigated: one- and two-channel statistical threshold techniques and multispectral visible and infrared approaches. Future work will be in areas of background and clear atmosphere characterization from infrared and microwave remote sensing, the addition of conventional cloud observations, customization of the analysis

based on regional location parameters, and manual interaction with automated nephelometer results.

Initial evaluation of algorithm results on selected case study data have shown significant improvement over the RTNEPH in detection of low cloud and fog, cirrus, and snow-cloud discrimination in polar regions. Problem areas that are being investigated further include incorrect modeling of background reflectance over ocean and desert, snow-cloud discrimination under conditions of low solar illumination, and the accuracy of supporting databases (e.g. surface skin temperatures, upper air profiles).

#### 6. ACKNOWLEDGEMENTS

This work is supported under contract F19628-90-C-0112 by the Geophysics Directorate, Phillips Laboratory (AFSC), Hanscom AFB, MA. The authors wish to acknowledge the work of Jean-Luc Moncet and Ron Isaacs of AER and Jim Bunting of the Geophysics Directorate for their valuable contributions to the cloud algorithm development effort. We would also like to thank Jeanne Sparrow, Dan Peduzzi, and Jim Belfiore for their hard work in coding the algorithms and analysis of the data.

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